Current Design Practice of Flexible Debris-resisting Barriers

Ir Harris Lam
Senior Geotechnical Engineer

Ir Dr Eric Sze
Geotechnical Engineer
Standards & Testing Division
Geotechnical Engineering Office

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- **Technical Development Works on Flexible Barriers by GEO** — Harris

- **Introduction of Flexible Barriers**

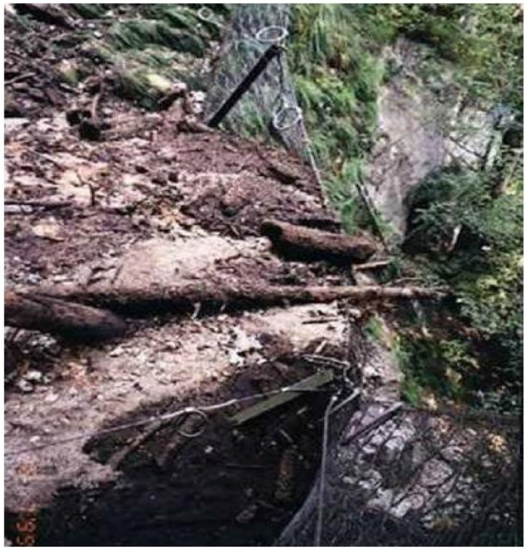
- **Current Local Design Practice**

(Introduction of Flexible Barriers; Current Local Design Practice) — Eric

Background (Global)

- Long history (>40 years) of using flexible barriers to resist rockfalls over the world. Occasionally, rockfall barriers were hit by landslide debris and able to stop/retain a certain amount of debris.
- Research of flexible barriers subject to debris impact has been emerging in the past decade. Internationally-recognized design guidelines are still limited.

1998: 750 m^3 debris flow in Japan (retained by 1500 kJ rockfall Barrier)



2000: 200 m^3 debris flow in Austria (retained by 750 kJ rockfall Barrier)

Background (Hong Kong)

- Implementation of LPMitP since 2010 triggered a series of technical development work by GEO on design of flexible barrier to resist debris flows in Hong Kong.

- Improved understanding on performance of flexible barriers has been made in recent years, largely due to availability of more field impact data, experimental data and advanced numerical tools that can simulate complex, highly non-linear debris-barrier interaction.

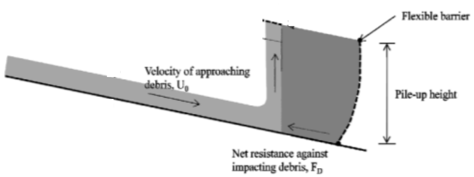
- Focus was given to establishing Design Approaches, with the aid of advanced numerical tools, for the design of flexible barriers to resist landslide debris.

Overview of Development on Design Approaches

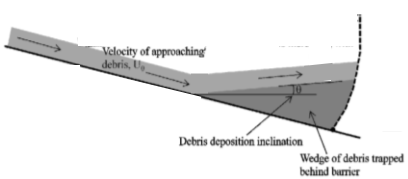
Stage 1 – Energy Approach (2010-2012)

Stage 2 – Force Approach (2012-2015)

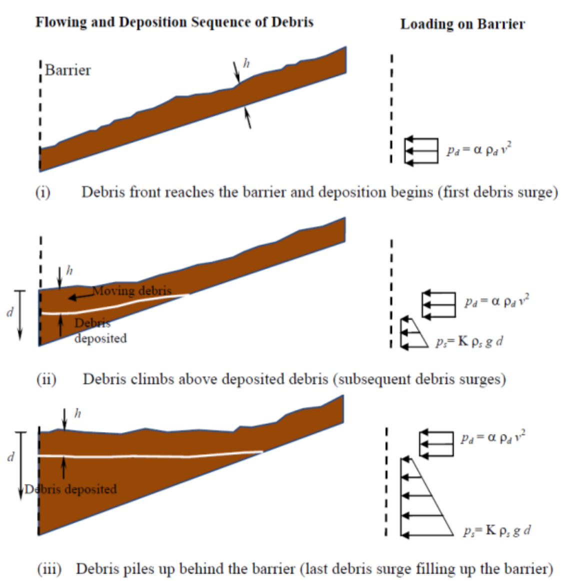
Stage 3 – Coupled Analyses using LS-DYNA (2015-2018)



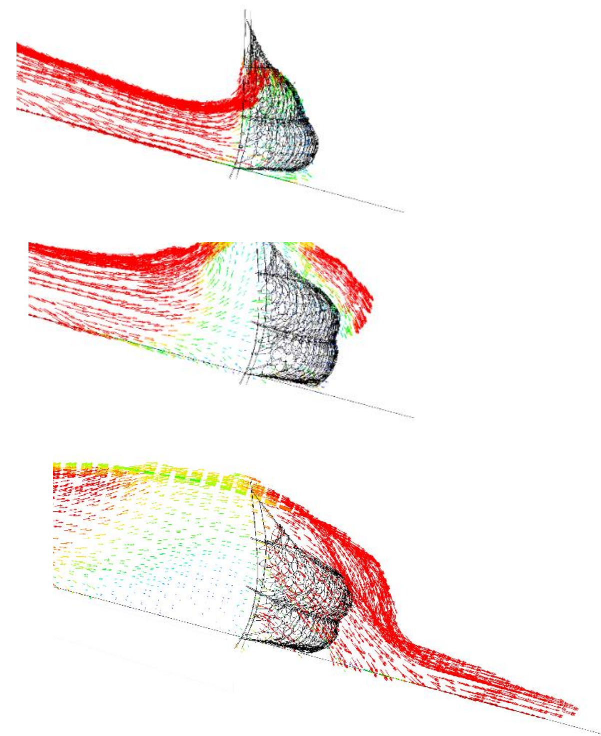
(a) Pile-up mechanism



(b) Run-up mechanism



$$p_d = \alpha \rho_d v^2$$



Stage 1 – Develop Energy Approach (2010-2012)

Stage 2 – Develop Force Approach (2012-2015)

Stage 3 – Development of Coupled Analyses using LS-DYNA (2015-2018)

Further Work

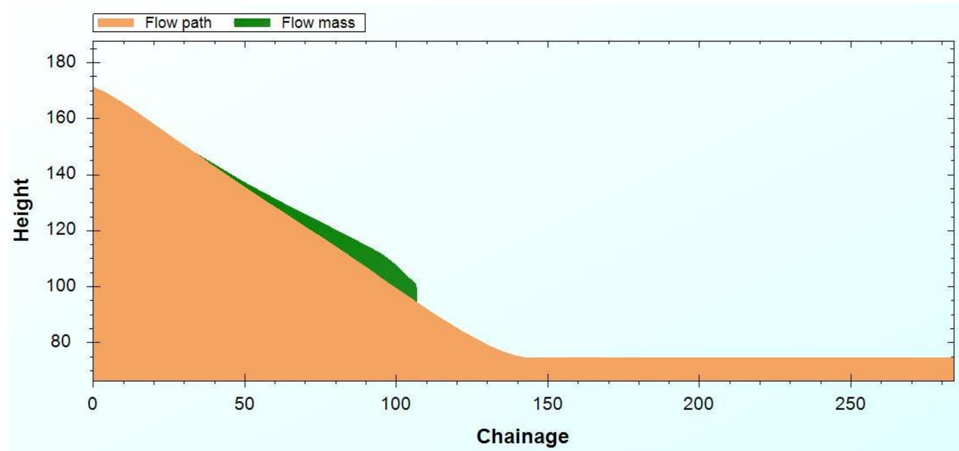
Dynamic Load Model

$$p_d = \alpha \rho_d v^2$$

ρ_d = density of moving debris

v = velocity of moving debris hitting the barrier (m/s)

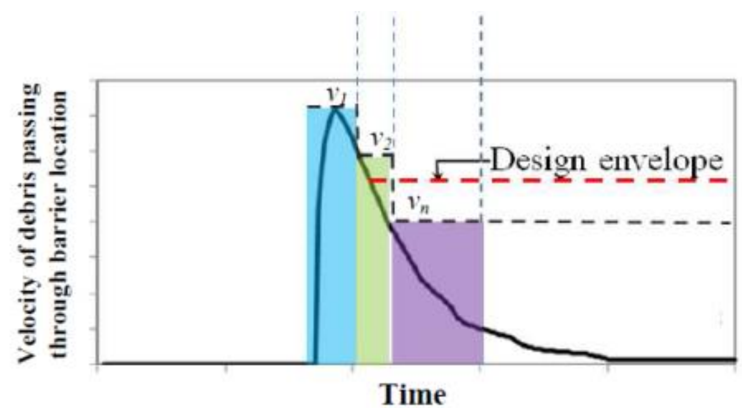
α = dynamic pressure coefficient, taken to be 2.0



Refined Assessment of design impact velocity (TGN 44)

observations of local landslide cases and physical flume test results suggest that debris velocity varies along the length of landslide debris

(c)



v_n = design impact velocity of the n^{th} phase ≮ 0.7 maximum debris velocity of the hydrograph

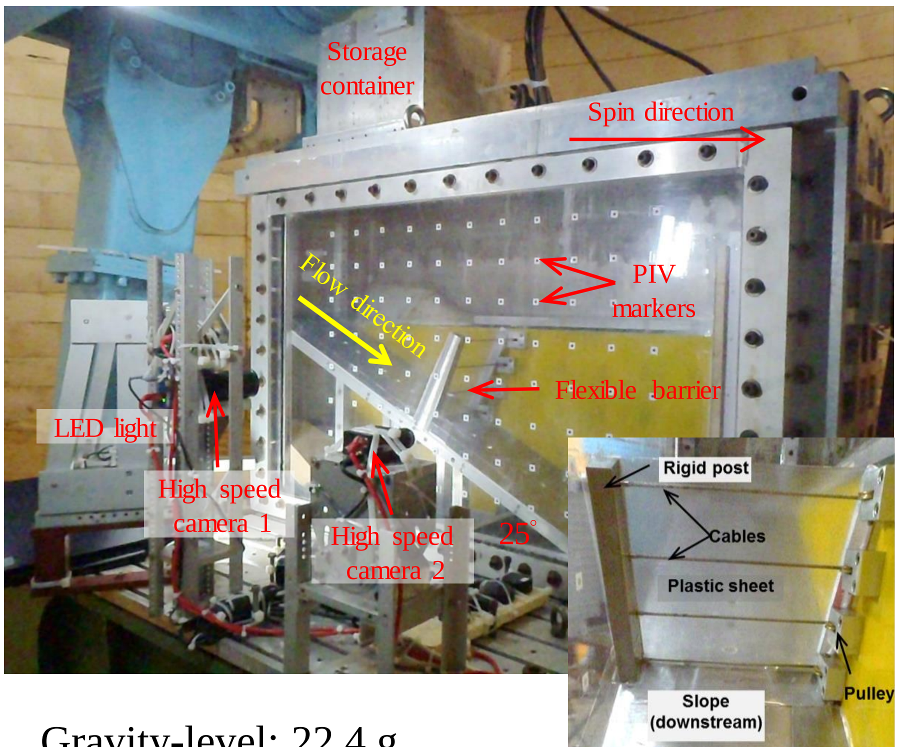
Stage 1 – Develop Energy Approach (2010-2012)

Stage 2 – Develop Force Approach (2012-2015)

Stage 3 – Development of Coupled Analyses using LS-DYNA (2015-2018)

Further Work

- **Centrifuge Tests to study dynamic pressure coeff. (α)**



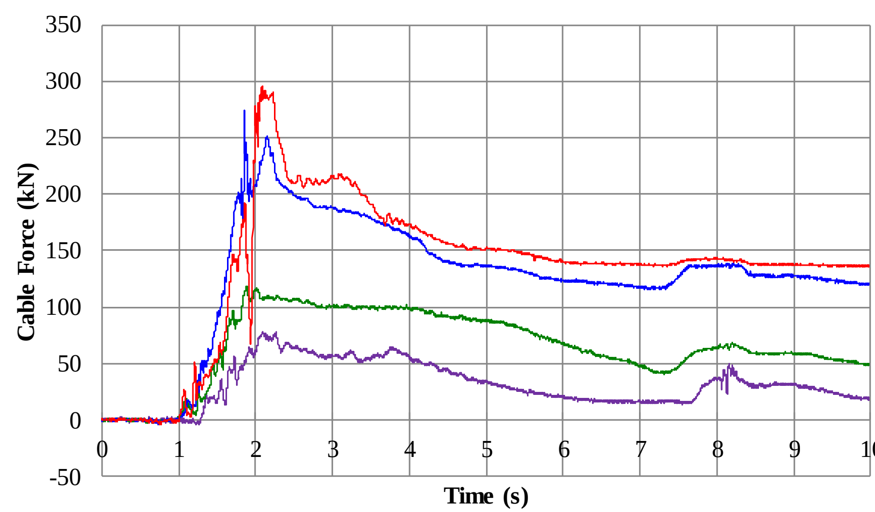
Gravity-level: 22.4 g
Debris volume: 170 m^3 (prototype)
Debris velocity: 9 – 22 m/s
Barrier height: 4.5 m (prototype)

Dynamic Load Model

$$p_d = \boxed{\alpha} \rho_d v^2$$

ρ_d = density of moving debris
v = velocity of moving debris hitting the barrier (m/s)
α = dynamic pressure coefficient, taken to be 2.0

Cable Force-Time History (FSL20)



For two-phase material, α = 0.7 – 1.3 (Song et al, 2018)

Rockfall Barriers Commonly Used in Hong Kong to Resist Debris Flow at Drainage Lines

Is there any better structural form of flexible barriers (other than those post-supported) for incised drainage lines?

Structural Forms of Flexible Barriers

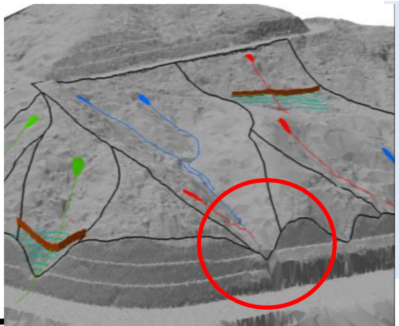
- Post-supported barriers are commonly used in Hong Kong

Open hillside

Drainage line

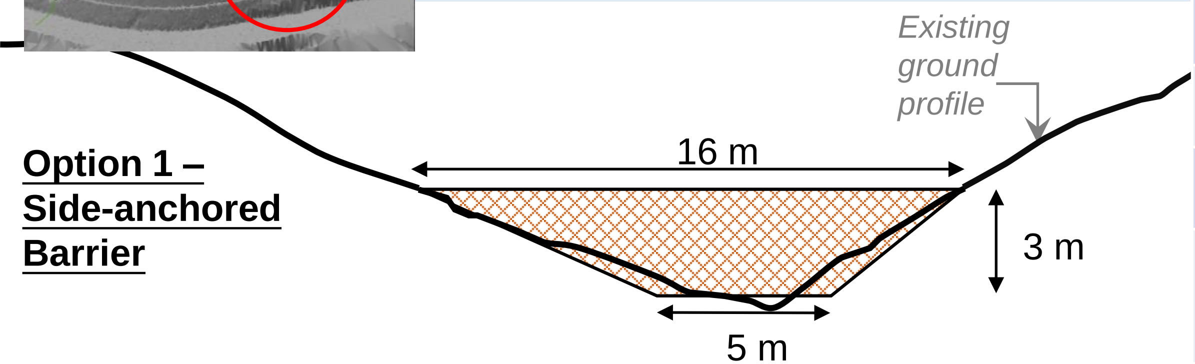
- Overseas project adopts side-anchored barriers in drainage lines

Comparison of Side-anchored barriers and post-supported barriers (for drainage line setting)

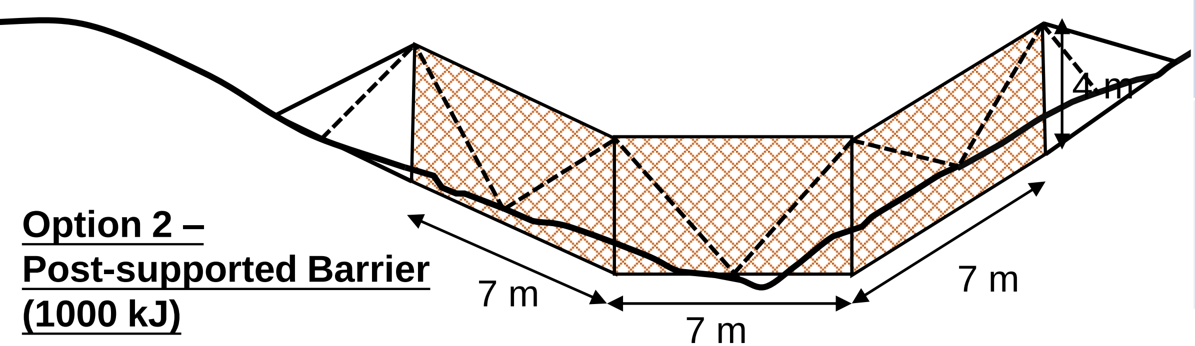


Flow thickness = 0.6 m
Debris impact velocity = 4 m/s
Debris impact energy = 534 kJ
Debris impact pressure = 70 kPa
Required retention volume = 100 m^3

Option 1 – Side-anchored Barrier

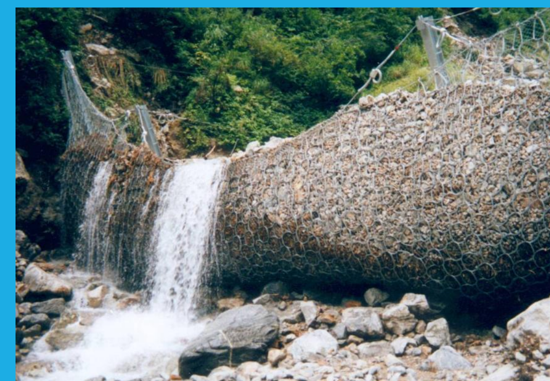


Option 2 – Post-supported Barrier (1000 kJ)



Design	Side-anchored Barrier (Option 1)	Post-supported Barrier (Option 2)
Principal Net area	30 m^3	80 m^3
Cable length	~80 m	> 200 m
Anchor points	8 nos.	15 nos.
Ease of installation	Simple (no heavy posts involved)	-
Maintenance	Lower (less materials used)	Higher (difficult access to upslope cables)
Environmental Impact	Less visual impact Less disturbance to environment	-

Structural Components and Load Path

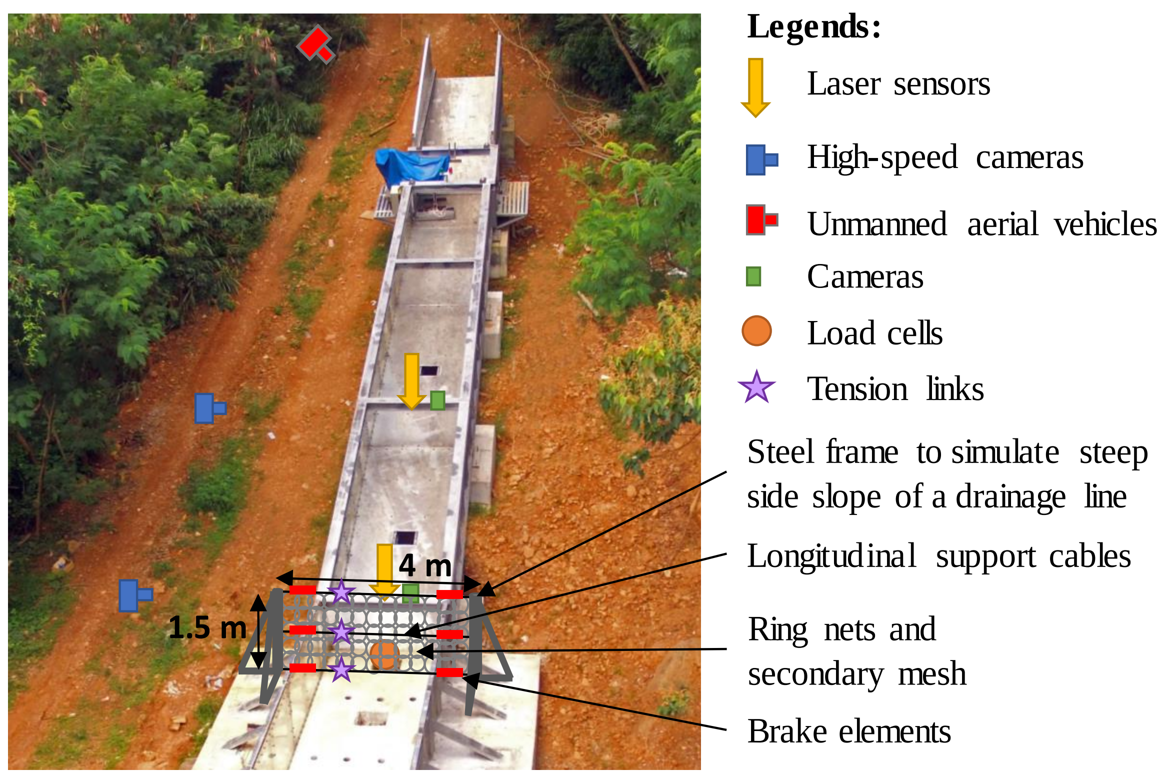
Side-anchored Barriers	Post-supported Barrier
	
Simple internal load-transfer net → cables & brakes → anchors	**More complex load-transfer** net → cables & brakes → anchors ↳ posts → upslope cables & brakes → anchors
No posts or upslope cables required	**Posts and upslope cables required** May be susceptible to direct debris impact

Yu Tung Road, Hong Kong (Jun 2008)

Localised damage of post (Trumer)

Test Plan to study Side-anchor Barriers in Hong Kong

(to be carried out in 2019)



Type 1 Barrier

- 0.8 m high x 2 m wide
- Test vol. 4 m3
- Test of overflow conditions

Type 2 Barrier

- 1.5 m high x 4 m wide
- Test vol. 10 m3

Improved Robustness of Post Supported barriers

Supporting post susceptible to localised damage due to boulder impact

Use of Baffles

Post Strengthening

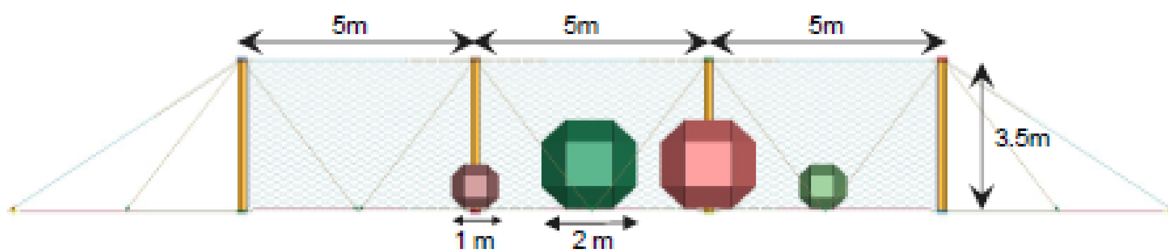
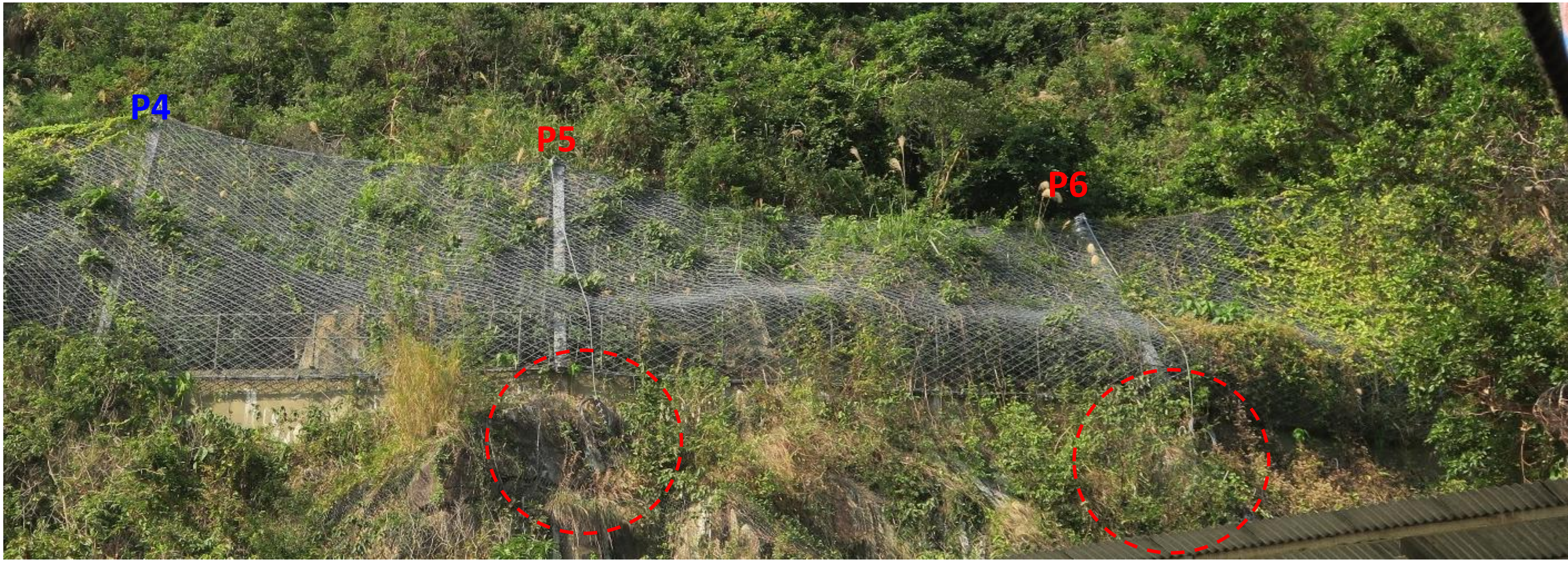


Fig. 40 Elevation of multi-boulders and the barrier model

One 2m size boulder is proposed to impact at the bottom-centre of the middle module of the barrier system. And another 2m size boulder is proposed to impact at the right-middle post. The two 1m size boulder are proposed to impact at the post and the centre of a module of barrier respectively.

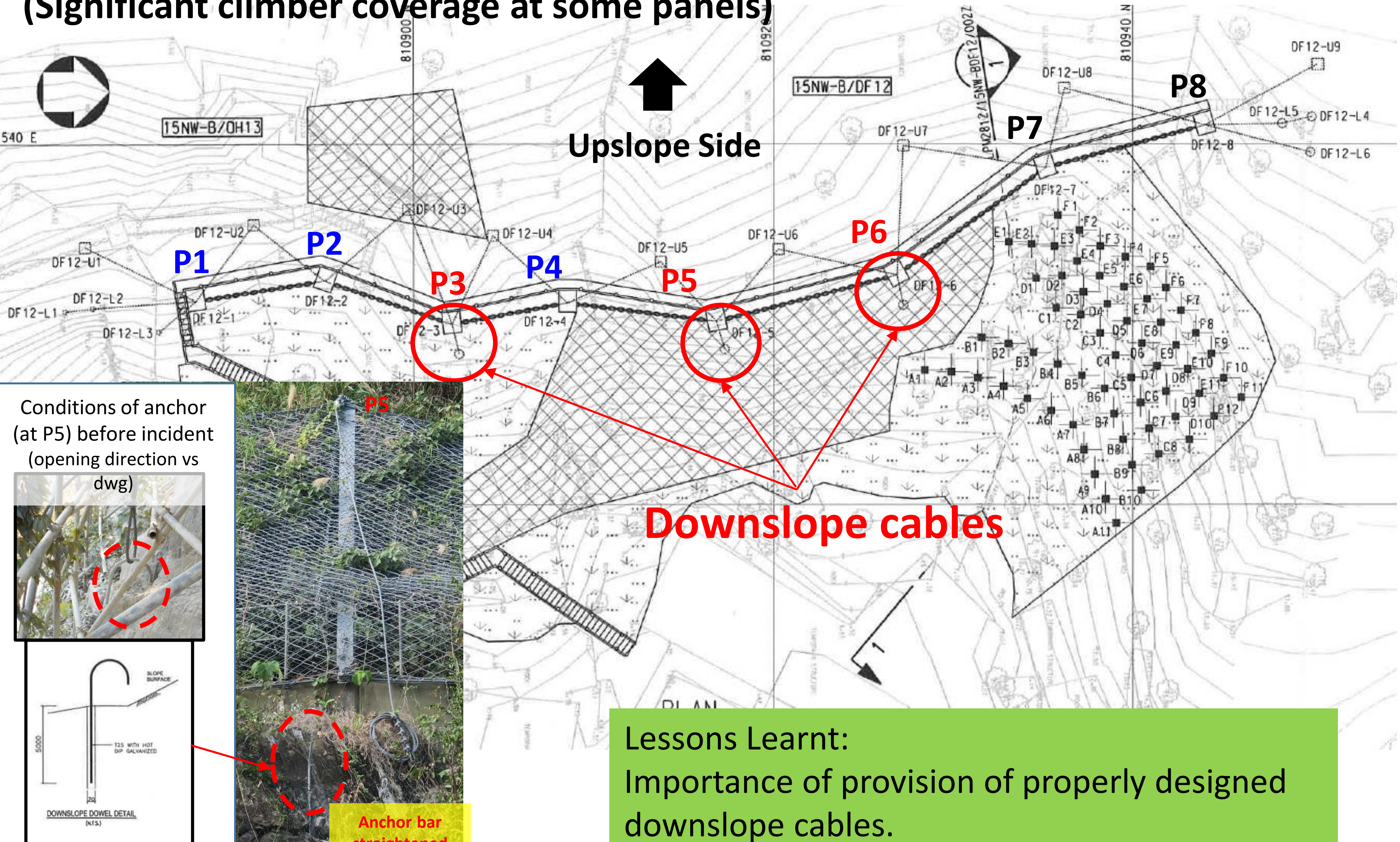
Wind Effect on Post-supported Barriers

- Overturning of barrier could occur under significant wind load.



As-built Information of ND12

ND12 (3000 kJ, 6 m x 62 m, 3 of 8 posts with downslope cables)
Netting: SPIDER+TECCO net + secondary mesh
(Significant climber coverage at some panels)

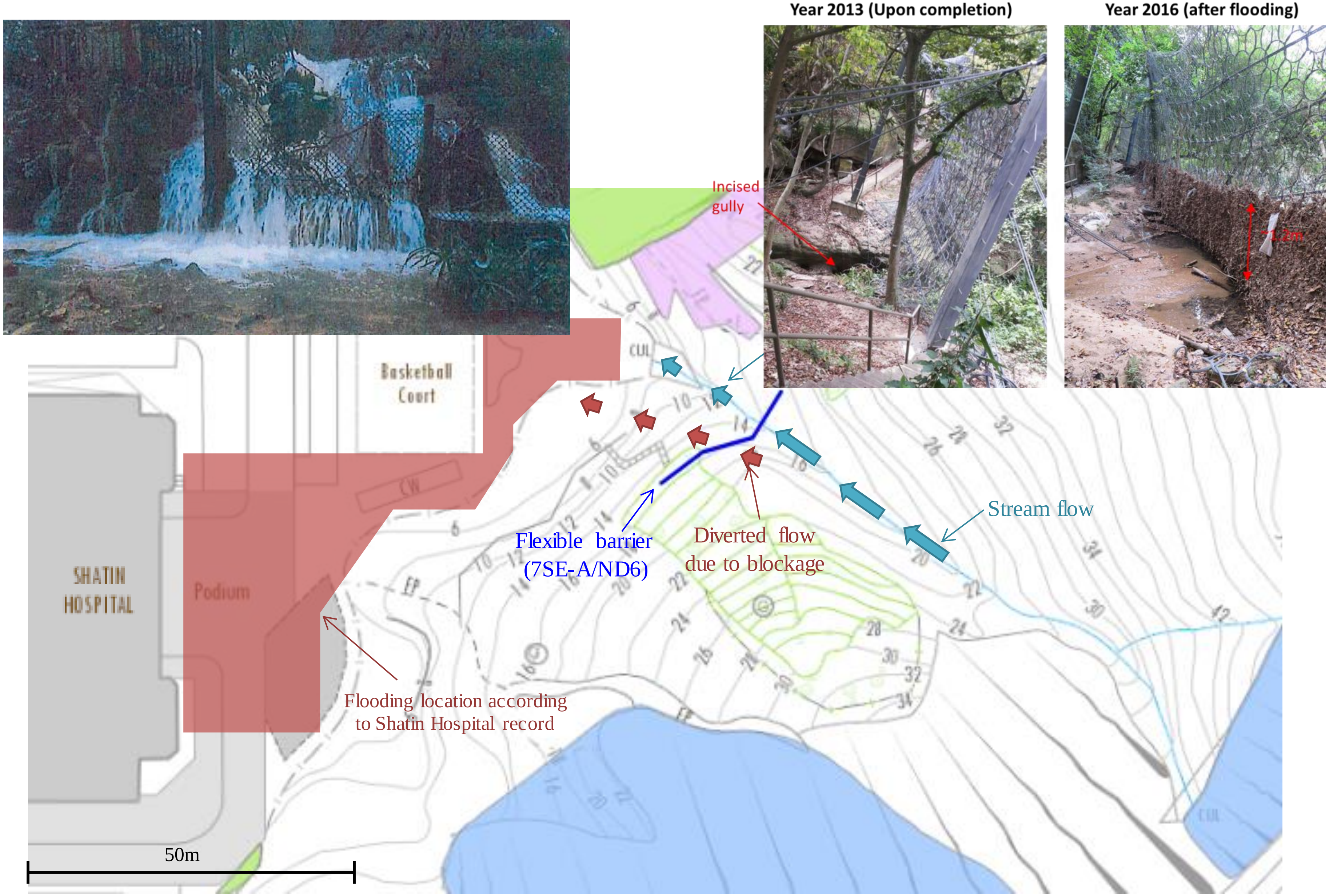


Conditions of anchor (at P5) before incident (opening direction vs dwg)

Anchor bar straightened

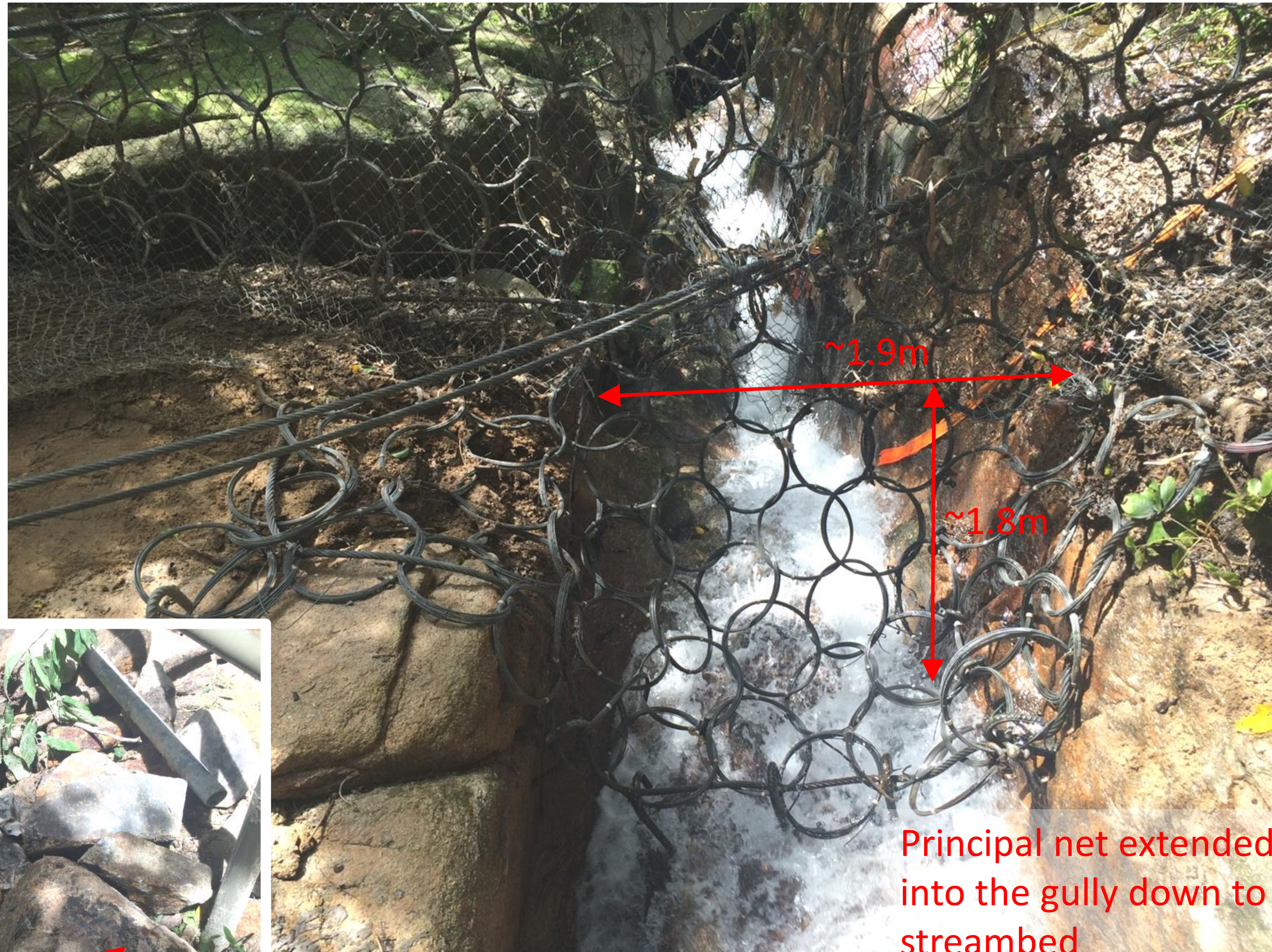
Lessons Learnt:
Importance of provision of properly designed downslope cables.

Detailing to prevent trapping of Stream load



CEDD Geotechnical Engineering Office, Civil Engineering and Development Department

Flexible Barrier above Shatin Hospital
(July 2017 – Debris Removed approx. 10 m³)

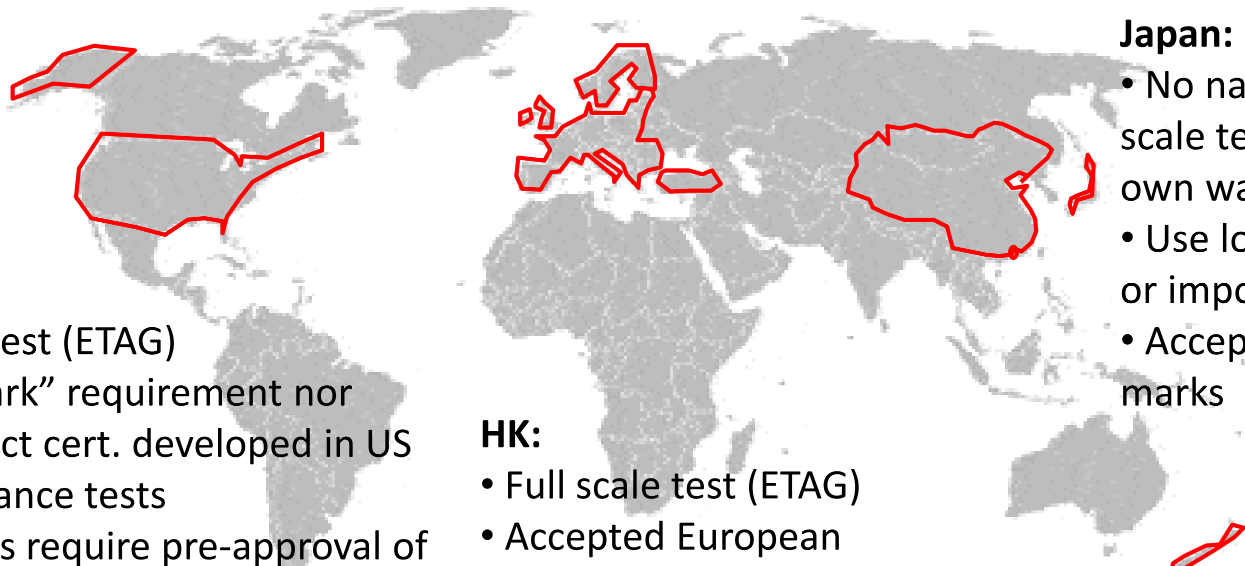


Bottom part of debris (~0.8m depth) comprised boulder-sized materials (~0.3 – 0.5m)

International Practice on Acceptance System

30+ countries in EU + Switzerland + Turkey :
- Full-scale test (ETAG)
- CE Mark
- No compliance tests

China:
- Full scale test by NRA (similar to ETAG 27)
- No CE Mark Requirement
- No similar product cert in China
- Component tests required in some projects



Japan:
- No national standard on full-scale test (each company use his own way to carry out tests)
- Use locally-developed barriers or import barriers from Europe
- Accept component with JIS marks

USA:
- Full-scale test (ETAG)
- No "CE Mark" requirement nor other product cert. developed in US
- No compliance tests
- Some states require pre-approval of suppliers (based on barrier's design, specification, full scale test report, job reference, etc.)

HK:
- Full scale test (ETAG)
- Accepted European products mostly delivered to HK with CE Mark
- Compliance Tests required

New Zealand:
- Full-scale test (ETAG)
- CE Mark not mandatory
- No compliance tests

Remarks:
- No standard international practices on acceptance of barriers
- ETAG is an internationally-recognized standard for full scale test.
- "CE Mark" is the only available product certification system for flexible barriers in the world.
- Other countries mainly import European barriers (with ETAG full-scale test proof) for local use, without compliance test (unlikely in HK).

European Practices - ETAG 27

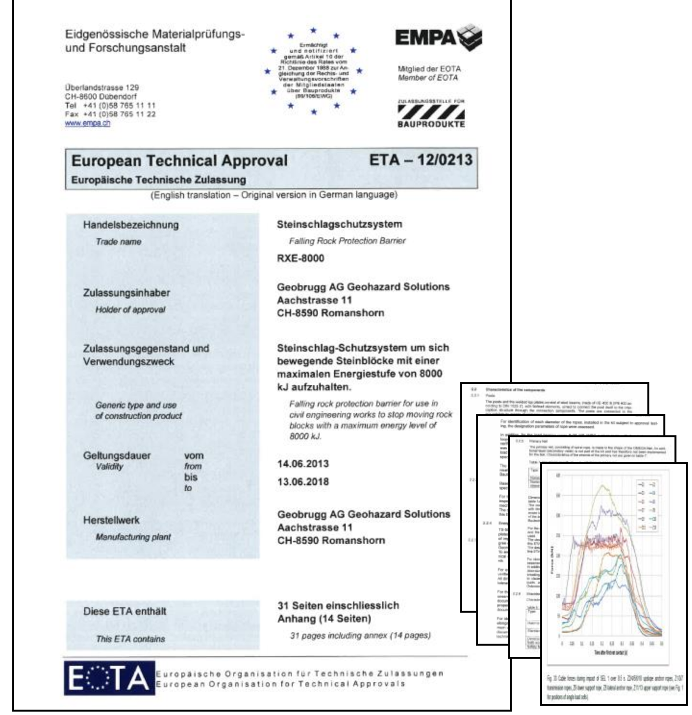
Full Scale test

0 Front view of the falling rock protection barrier GBE-8000A after MEL test (29.11.2011).

1 Bottom view of the falling rock protection barrier GBE-8000A after MEL test.

Technical Assessment Body (TAB)

- Supervise and certify full scale test
- Assessment covers Barrier's Characteristics including energy absorption, deformation, foundation loads, durability, etc.
- Issue an evaluation report and ETA Certificate



Eidgenössische Materialprüfungs- und Forschungsanstalt

Überlandstrasse 129
CH-8600 Dübendorf
Tel +41 (0)58 765 11 11
Fax +41 (0)58 765 11 22
www.empa.ch

EMPA

Mitglied der EOTA
Member of EOTA

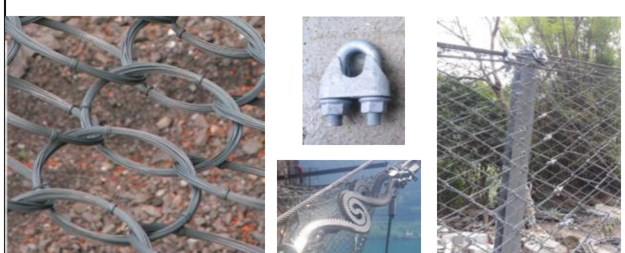
BAUPRODUKTE

European Technical Approval ETA – 12/0213
Europäische Technische Zulassung
(English translation – Original version in German language)

Handelsbezeichnung *Trade name*	Steinschlagschutzsystem *Falling Rock Protection Barrier* RXE-8000
Zulassungsinhaber *Holder of approval*	Geobrugg AG Geohazard Solutions Aachstrasse 11 CH-8590 Romanshorn
Zulassungsgegenstand und Verwendungszweck *Generic type and use of construction product*	Steinschlag-Schutzsystem um sich bewegende Steinblöcke mit einer maximalen Energiestufe von 8000 kJ aufzuhalten. *Falling rock protection barrier for use in civil engineering works to stop moving rock blocks with a maximum energy level of 8000 kJ.*
Geltungsdauer vom / bis *Validity from / to*	14.06.2013 13.06.2018
Herstellwerk *Manufacturing plant*	Geobrugg AG Geohazard Solutions Aachstrasse 11 CH-8590 Romanshorn
Diese ETA enthält *This ETA contains*	31 Seiten einschliesslich Anhang (14 Seiten) *31 pages including annex (14 pages)*

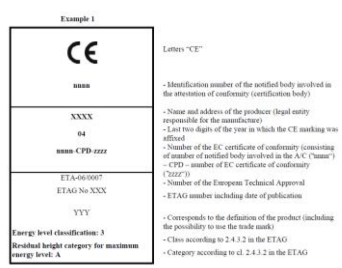
EOTA
Europäische Organisation für Technische Zulassungen
European Organisation for Technical Approvals

Factory Production Control



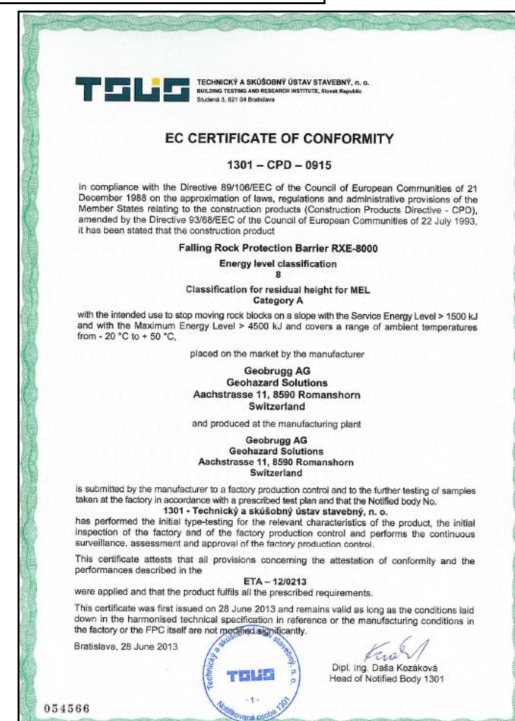
Certification Body ("Notified Body")

-Initial type-test of product
-Initial factory inspection and production control
-Continuous surveillance (once a year), assessment and approval of factory production control



Example 1

CE	Letters "CE"
nnnn	- Identification number of the notified body involved in the attestation of conformity (certification body)
XXXX 04 nnnn-CPD-zzzz	- Name and address of the producer (legal entity responsible for the manufacture) - Last two digits of the year in which the CE marking was affixed - Number of the EC certificate of conformity (consisting of number of notified body involved in the A/C ("nnnn") - CPD – number of EC certificate of conformity ("zzzz"))
ETA-06/0007 ETAG No XXX	- Number of the European Technical Approval - ETAG number including date of publication
YYY	- Corresponds to the definition of the product (including the possibility to use the trade mark)
Energy level classification: 3 Residual height category for maximum energy level: A	- Class according to 2.4.3.2 in the ETAG - Category according to cl. 2.4.3.2 in the ETAG



TSUS TECHNICKÝ A SKÚŠOBNÝ ÚSTAV STAVEBNÝ, n. o.
BUILDING TESTING AND RESEARCH INSTITUTE, Slovak Republic
Studená 3, 821 04 Bratislava

EC CERTIFICATE OF CONFORMITY

1301 – CPD – 0915

In compliance with the Directive 89/106/EEC of the Council of European Communities of 21 December 1988 on the approximation of laws, regulations and administrative provisions of the Member States relating to the construction products (Construction Products Directive - CPD), amended by the Directive 93/68/EEC of the Council of European Communities of 22 July 1993, it has been stated that the construction product

Falling Rock Protection Barrier RXE-8000
Energy level classification
8
Classification for residual height for MEL
Category A

with the intended use to stop moving rock blocks on a slope with the Service Energy Level > 1500 kJ and with the Maximum Energy Level > 4500 kJ and covers a range of ambient temperatures from - 20 °C to + 50 °C,

placed on the market by the manufacturer

Geobrugg AG
Geohazard Solutions
Aachstrasse 11, 8590 Romanshorn
Switzerland

and produced at the manufacturing plant

Geobrugg AG
Geohazard Solutions
Aachstrasse 11, 8590 Romanshorn
Switzerland

is submitted by the manufacturer to a factory production control and to the further testing of samples taken at the factory in accordance with a prescribed test plan and that the Notified body No.
1301 - Technický a skúšobný ústav stavebný, n. o.
has performed the initial type-testing for the relevant characteristics of the product, the initial inspection of the factory and of the factory production control and performs the continuous surveillance, assessment and approval of the factory production control.

This certificate attests that all provisions concerning the attestation of conformity and the performances described in the
ETA – 12/0213
were applied and that the product fulfils all the prescribed requirements.

This certificate was first issued on 28 June 2013 and remains valid as long as the conditions laid down in the harmonised technical specification in reference or the manufacturing conditions in the factory or the FPC itself are not modified significantly.

Bratislava, 28 June 2013

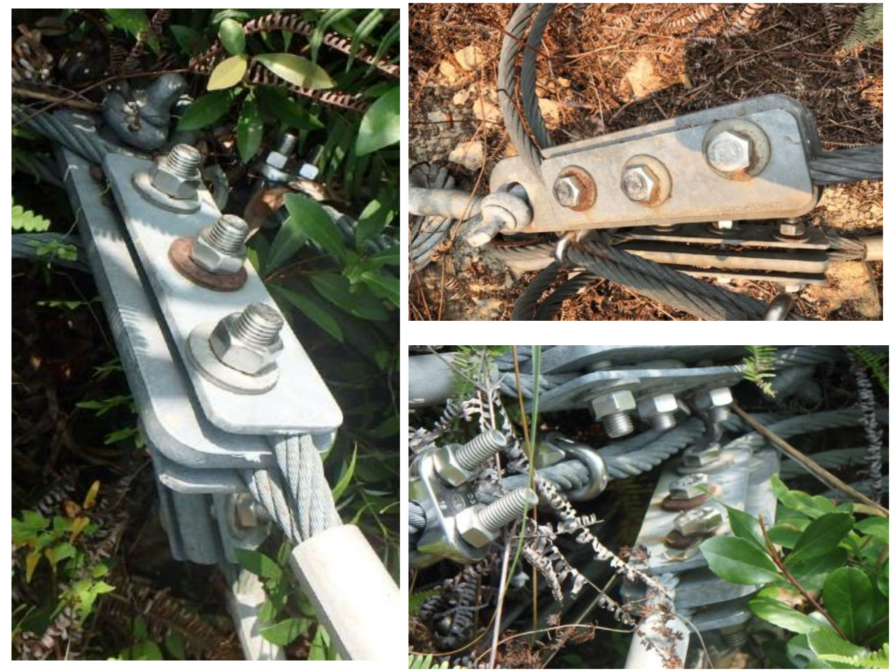
Dipl. Ing. Daša Kozáková
Head of Notified Body 1301

054566

Maintenance Strategy -
Condition Review of Flexible Barriers

No Rusting

Bay no.	Post (m2)	Ground plate (nr)	Principal net (m2)	Anchor (nr)	Energy - dissipating device (nr)	Wire rope (m)	Shackle (nr)	Wire rope clip (nr)	Others Thimble (nr)
Bay 1	2	0	50	4	4	112	12	74	11
Bay 2	1	0	50	1	1	67	9	48	6
Bay 3	1	1	50	1	2	63	9	47	6
Bay 4	1	1	50	1	1	67	9	48	6
Bay 5	1	0	50	1	2	67	9	48	6
Bay 6	1	1	50	1	2	67	9	48	6
Bay 7	1	1	50	3	3	107	11	72	11
Subtotal	8	4	350	12	15	550	68	385	52
%	100%	50%	100%	100%	47%	99%	100%	99%	58%



Signs of Minor Rusting at brake element

Minor Rusting

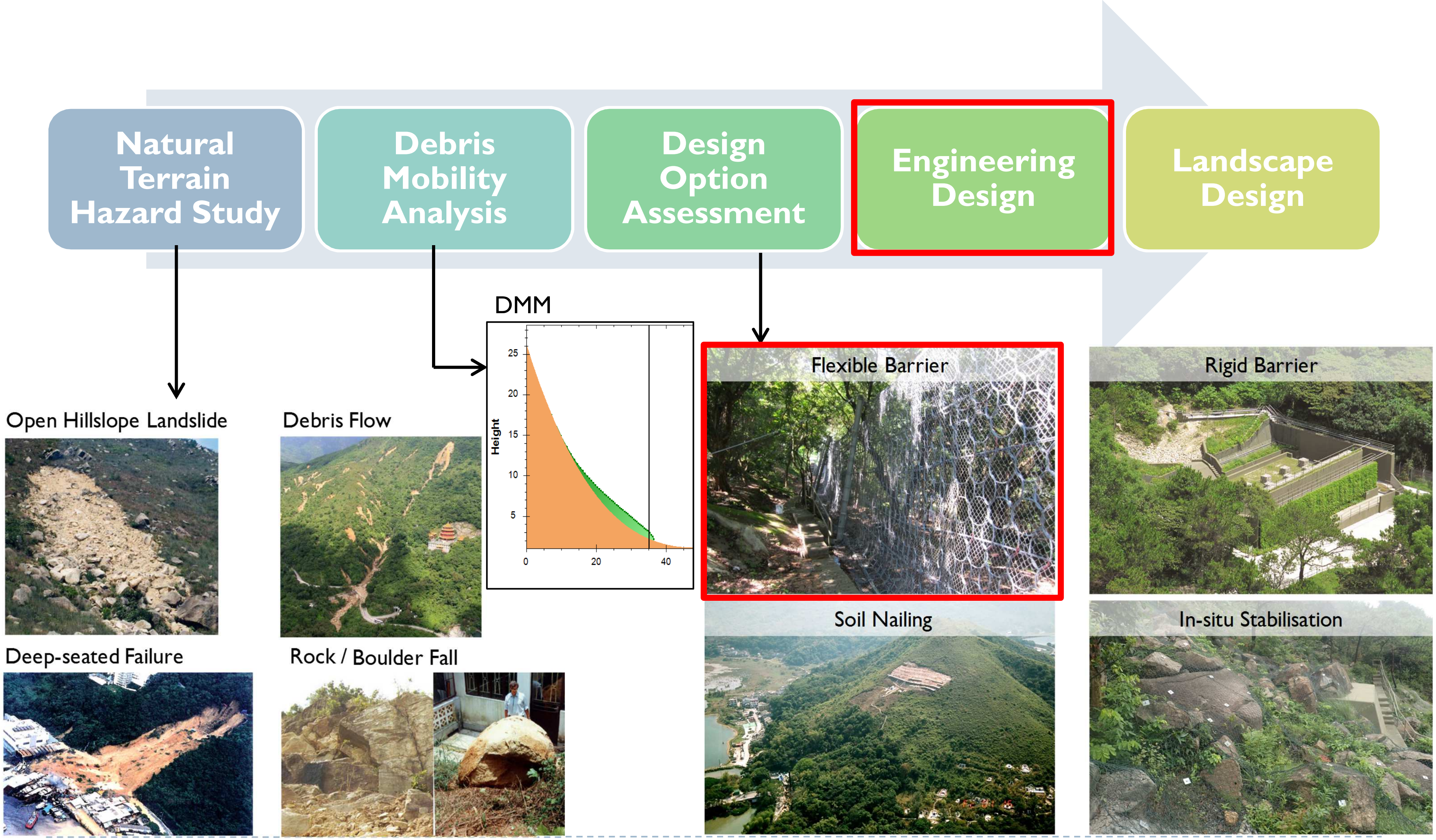
Bay no.	Post (m2)	Ground plate (nr)	Principal net (m2)	Anchor (nr)	Energy - dissipating device (nr)	Wire rope (m)	Shackle (nr)	Wire rope clip (nr)	Others - Thimble (nr)
Bay 1	0	2	0	0	2	0	0	2	0
Bay 2	0	1	0	0	3	0	0	0	0
Bay 3	0	0	0	0	2	4	0	1	0
Bay 4	0	0	0	0	3	0	0	0	0
Bay 5	0	1	0	0	2	0	0	0	0
Bay 6	0	0	0	0	2	0	0	0	0
Bay 7	0	0	0	0	3	0	0	0	2
Subtotal	0	4	0	0	17	4	0	3	2
%	0%	50%	0%	0%	53%	1%	0%	1%	2%

Shackles

Overall Summary

- GEO would continue to carry out technical development work on the following, with a view to enhancing the design and maintenance standards of debris-resisting flexible barriers in Hong Kong.
    - Design approach
    - Structural form
    - Detailing
    - Acceptance Systems
    - Maintenance Strategy

Typical Design Flowchart for Natural Terrain Mitigation Measures



Working principle of flexible barriers

Source: Geobrugg, St Leonard Field Test

Source: Trumer, Rockfall Impact Test

- Mitigate landslide hazards by capturing the materials and resisting the impact
- Dissipate the impact energy by large deformation of the system and / or mobilisation of energy-dissipating devices

Typical components

Principal net

Secondary mesh

Wire ropes

Post

Brake elements

Anchor foundation

Variations among products

Principal Net

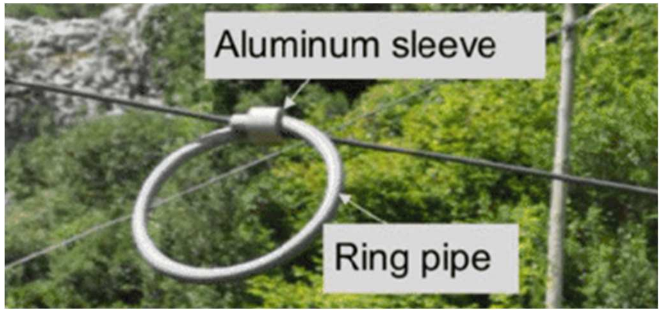
Geobrugg

Trumer (2013)

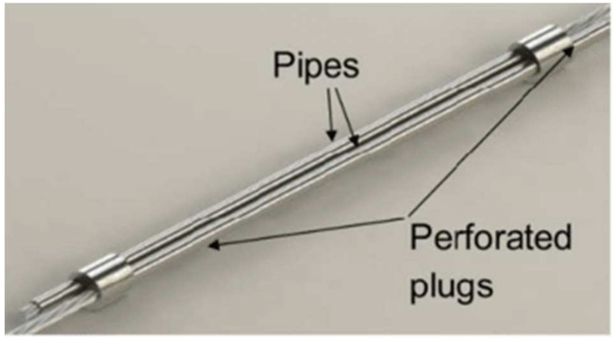
Isofer (2012)

Others such as cable and brake element arrangement, post and anchor head connection details, etc.

Brake Elements



Geobrugg



Maccaferri

Trumer

Rockfall flexible barriers

- Energy rating certified by full-scale impact tests
- Designed by Empirical Approach or Analytical Approach

Maccaferri RMC 300A (3000kJ)

Trumer TSC-3000-ZD (3000kJ)

Geobrugg RXE-5000 (5000kJ)

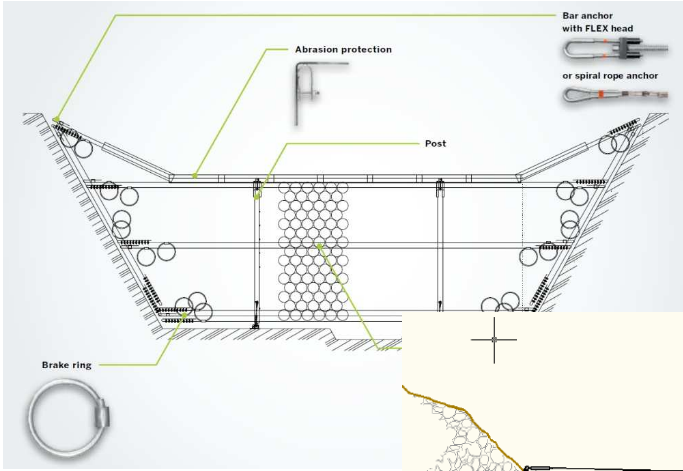
Geobrugg RXE-8000 (8000kJ)

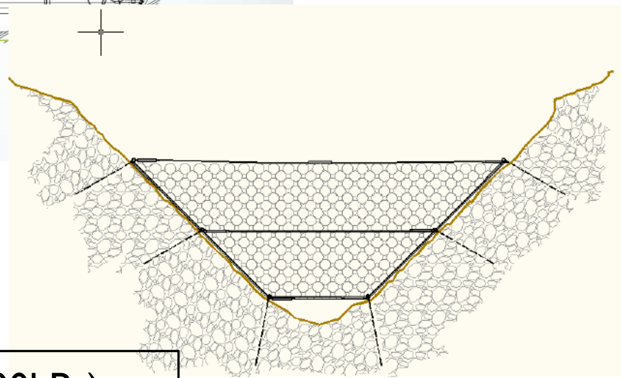
Trumer (2013)

Ref.: https://www.geobrugg.com/en/Downloads-8113,7849.html?filter_ordner=9400&formular_submit=1

Debris-resisting flexible barriers

- Pressure rating certified by full-scale impact tests & numerical analyses
- Usually require site-specific design using Analytical Approach





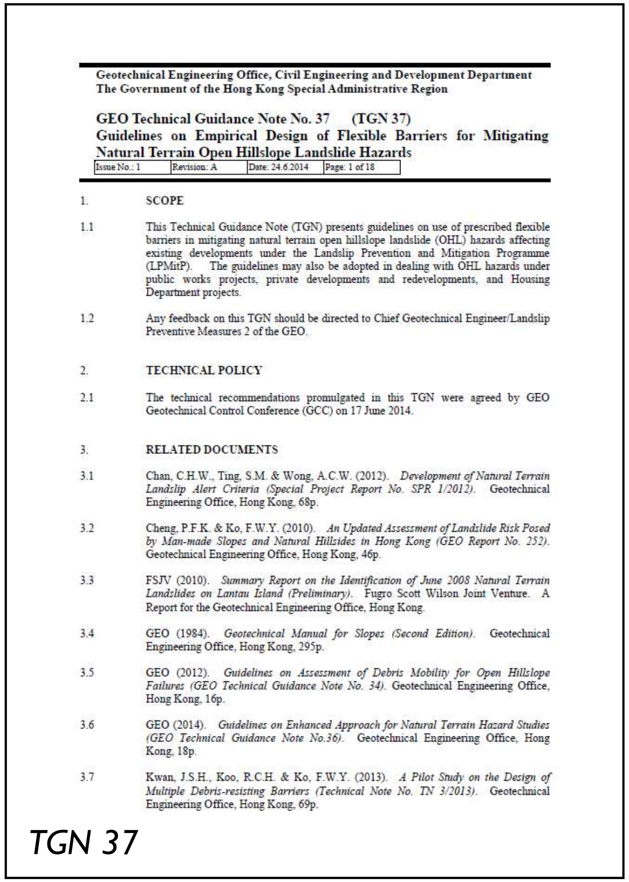
Geobrugg VX Barrier (60-160kPa)

Maccaferri DF Barrier (80-200kPa)

Maccaferri (2011)

Ref.: https://www.geobrugg.com/en/Downloads-8113,7849.html?filter_ordner=9400&formular_submit=1

Local design practice



Geotechnical Engineering Office, Civil Engineering and Development Department
The Government of the Hong Kong Special Administrative Region

GEO Technical Guidance Note No. 37 (TGN 37)
Guidelines on Empirical Design of Flexible Barriers for Mitigating Natural Terrain Open Hillslope Landslide Hazards

Issue No.: 1	Revision: A	Date: 24.6.2014	Page: 1 of 18

1. SCOPE

1.1 This Technical Guidance Note (TGN) presents guidelines on use of prescribed flexible barriers in mitigating natural terrain open hillslope landslide (OHL) hazards affecting existing developments under the Landslip Prevention and Mitigation Programme (LPMitP). The guidelines may also be adopted in dealing with OHL hazards under public works projects, private developments and redevelopments, and Housing Department projects.

1.2 Any feedback on this TGN should be directed to Chief Geotechnical Engineer/Landslip Preventive Measures 2 of the GEO.

2. TECHNICAL POLICY

2.1 The technical recommendations promulgated in this TGN were agreed by GEO Geotechnical Control Conference (GCC) on 17 June 2014.

3. RELATED DOCUMENTS

3.1 Chan, C.H.W., Ting, S.M. & Wong, A.C.W. (2012). *Development of Natural Terrain Landslip Alert Criteria (Special Project Report No. SPR 1/2012).* Geotechnical Engineering Office, Hong Kong, 68p.

3.2 Cheng, P.F.K. & Ko, F.W.Y. (2010). *An Updated Assessment of Landslide Risk Posed by Man-made Slopes and Natural Hillsides in Hong Kong (GEO Report No. 252).* Geotechnical Engineering Office, Hong Kong, 46p.

3.3 FSJV (2010). *Summary Report on the Identification of June 2008 Natural Terrain Landslides on Lantau Island (Preliminary).* Fugro Scott Wilson Joint Venture. A Report for the Geotechnical Engineering Office, Hong Kong.

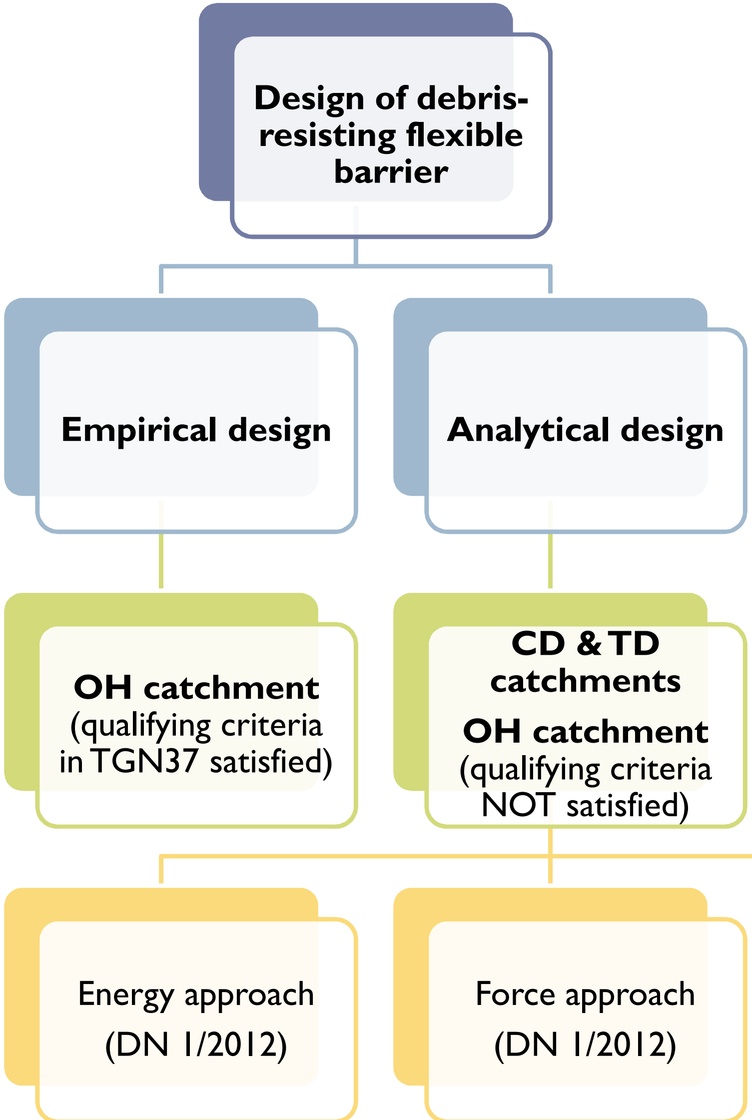
3.4 GEO (1984). *Geotechnical Manual for Slopes (Second Edition).* Geotechnical Engineering Office, Hong Kong, 295p.

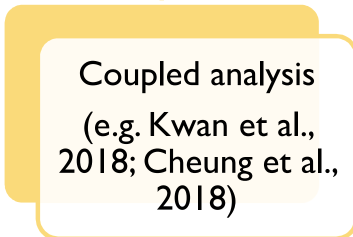
3.5 GEO (2012). *Guidelines on Assessment of Debris Mobility for Open Hillslope Failures (GEO Technical Guidance Note No. 34).* Geotechnical Engineering Office, Hong Kong, 16p.

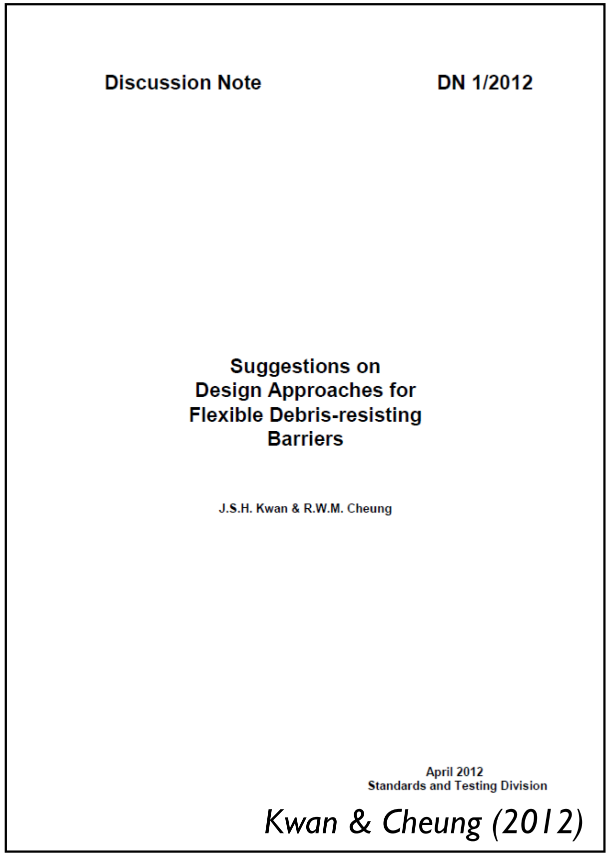
3.6 GEO (2014). *Guidelines on Enhanced Approach for Natural Terrain Hazard Studies (GEO Technical Guidance Note No.36).* Geotechnical Engineering Office, Hong Kong, 18p.

3.7 Kwan, J.S.H., Koo, R.C.H. & Ko, F.W.Y. (2013). *A Pilot Study on the Design of Multiple Debris-resisting Barriers (Technical Note No. TN 3/2013).* Geotechnical Engineering Office, Hong Kong, 69p.

TGN 37







Discussion Note DN 1/2012

Suggestions on Design Approaches for Flexible Debris-resisting Barriers

J.S.H. Kwan & R.W.M. Cheung

April 2012
Standards and Testing Division

Kwan & Cheung (2012)

Empirical design approach (TGN 37)

- Applicable against OHL hazard
- Can be adopted if
  - It is for holistic risk mitigation, or
  - The following qualifying criteria are satisfied:

Qualifying Criteria for Using the Empirical Design Approach

5.2 The empirical design approach should generally only be applied to OH catchments (or sub-catchments) that satisfy the following criteria:

(a) Within a plan distance of 100 m from the affected facilities, no recent landslide with a volume greater than 100 m^3, and no recent landslide with a volume between 50 m^3 and 100 m^3 with debris reaching closer than 20 m on plan from the affected facilities, has occurred on the OH catchment.

(b) Within a plan distance of 100 m from the affected facilities, no continuous steeply inclined ground surface of more than 40° in gradient and 40 m in length on plan along a runout path is present on the OH catchment.

(c) There is no evidence of existing significant signs of distress, continuing hazardous movement or incipient instability within the OH catchment, which could affect a facility covered by the facility types given in Table 1. Appropriate mitigation measures should be designed to address the hazards from such features.

(d) No newly emerged hazardous situation has evolved as a result of the occurrence of new landslide(s) (e.g. landslides which occurred during the course of NTHS), development of new signs of distress and hazardous movement, or exacerbation of existing signs of distress and hazardous movement on the OH catchment, particularly where there is concern of further hillside deterioration leading to instability.

(e) The OH catchment is not susceptible to deep-seated landslide hazards.

Table 1 – Empirical design of prescribed flexible barrier against OHL hazard

Facility	Proximity		
	Very Close (e.g. if angular elevation from the facility is ≥ 30°)	Moderately Close (e.g. if angular elevation from the facility is <30° and ≥ 25°)	Far (e.g. if angular elevation from the facility is < 25°)
Buildings and sensitive structures[2]	R1 + baffles	R1	R3
Groups 1&2 other than buildings and sensitive structures	R1	R2	Nil
Group 3	R2	R3	Nil

Notes:

(1) The facility group and proximity class should be assessed following the guidelines given in GEO Report No. 138.

(2) Sensitive structures refer to those facilities including Potential Hazardous Installations, tunnel portal, petrol station, railway platform and MTR exit that may involve severe consequence when affected by landslides, in accordance with the facility classification adopted in GEO Report No. 191.

(3) If boulder/rock fall hazards also exist, the kinetic energy of the boulder/rock hitting the barrier should not exceed the energy rating of the barrier, and the corresponding bounce height of the boulder/rock should not exceed the height of the barrier.

(4) R1: 3,000 kJ flexible rock fall barrier with minimum height of 4 m.
R2: 2,000 kJ flexible rock fall barrier with minimum height of 3 m.
R3: 1,000 kJ flexible rock fall barrier with minimum height of 3 m.

(5) 'Baffles' comprise structural steel sections or steel hollow sections filled with concrete placed in rows uphill of the flexible barrier. They are prescribed measures for enhancing the robustness of the mitigation scheme, by reducing the impact force/energy of the landslide debris reaching the barriers and facilitating debris deposition.

(6) A suitable clearance between the barrier and the affected facility should be provided to allow for deformation of the barrier upon hitting by landslide debris/boulder/rock.

(7) The stability of the hillside/slopes below the barrier including the effects of the foundations of the barrier on their stability should be assessed.

Analytical design approach

- Can be adopted if it is for mitigating
  - OHL hazards where the qualifying criteria cannot be met
  - Debris flow hazards

- Three approaches
  - Energy approach (Kwan & Cheung, 2012; Sun & Law, 2015)
  - Force approach (Kwan & Cheung, 2012; Sze et al., 2018)
  - Coupled analysis (e.g. Kwan et al., 2018; Cheung et al., 2018)

Energy Approach

- Key design consideration:

Energy Dissipation Capacity (EDC) of barrier > Energy loading (E) of debris flow

- **Calculation of "E"**
  - What is the energy brought by debris flow to a flexible barrier?

** There is internal energy dissipation as the debris flows & interacts with the barrier*

$$E < \frac{1}{2} m_{total} v_{max}^2$$

Determine Energy Loading "E"

Step 1
Carry out debris mobility assessment

→ Calculate the flow velocity and depth hydrograph at the design location of flexible barrier (TGNs 29, 34, 38)

Step 2a
Calculate impact energy with assuming pile-up mechanism (E_p)

1. Check T_s according to TN 1/2012 Equation 6.11a

$$T_s = \frac{\gamma U_0}{(\mu \cos\theta \ - \ \sin\theta)\, g}$$

2. If $0 < T_s \leq V / U_o$, calculate E_p according to TN 1/2012 Equation 6.13a

$$E_p = \frac{\gamma \rho Q_0 U_0^3}{4\,(\mu \cos\theta \ - \ \sin\theta)\, g}$$

If $T_s \geq V / U_o$ then $E_p = E_k$

where
- γ = dynamic pressure coefficient
- U_o = debris impact velocity (m/s)
- θ = inclination of channel base behind the barrier
- μ = basal friction coefficient (i.e. tanϕ)
- g = gravitational acceleration (m/s^2)
- ρ = bulk density of the landslide debris deposit (kg/m^3)
- Q_o = discharge rate (m^3/s)
- V = debris volume (m^3)
- T_s = impact duration (s)
- E_k = kinetic energy of the entire landslide debris mass (J)

Step 2b
Calculate impact energy with assuming run-up mechanism (E_r) according to TN 1/2012 Equation 6.19

$$E_r = \frac{\rho Q_0 U_0^5 \cos(\theta+\alpha) \sin(\theta+\alpha)}{48\, h_0\, g^2 (\mu \cos\alpha + \sin\alpha)^2}$$

where
- h_0 = debris depth (m)
- α = inclination of ramp formed by debris accumulated behind flexible barrier
- U_o = debris impact velocity (m/s)
- θ = inclination of channel base behind the barrier
- μ = basal friction coefficient (i.e. tanϕ)
- g = gravitational acceleration (m/s^2)
- ρ = bulk density of the landslide debris deposit (kg/m^3)
- Q_o = discharge rate (m^3/s)

→ Calculate the upper bound impact energy based on pile-up and run-up mechanisms (GEO Report 309)

Step 3
Calculate kinetic energy of the entire landslide debris mass (E_k)

$$E_k = \max\,(E_{k1}, E_{k2})$$

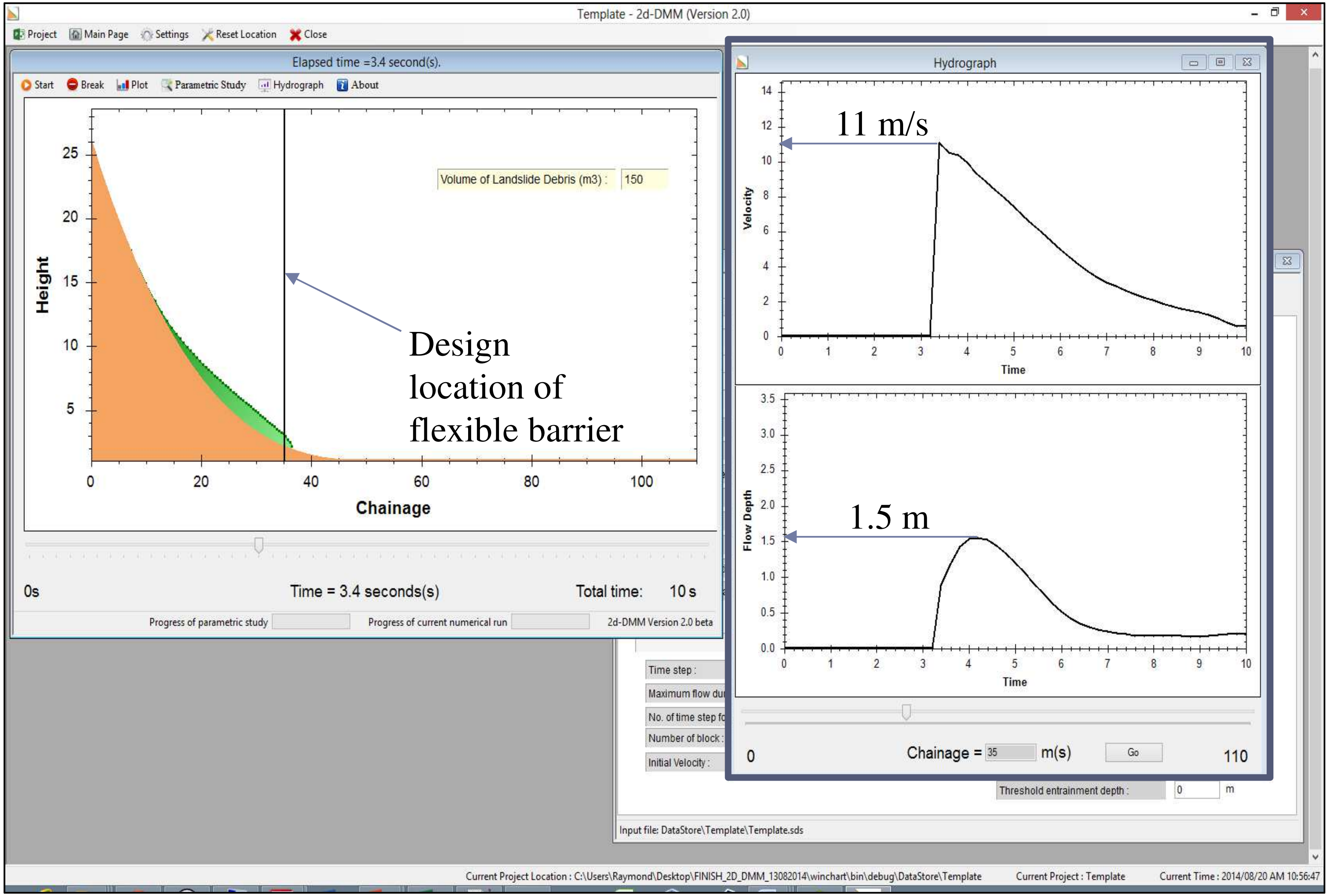
E_{k1} = kinetic energy of landslide debris when the debris front reaches the barrier location
E_{k2} = kinetic energy of landslide debris that travelled beyond the barrier location

→ Calculate the upper bound energy requirements by assuming no energy loss

Step 4
Energy loading $E = \min\,(E_k, \max(E_p, E_r))$
(DN 1/2012 Equation B.4)

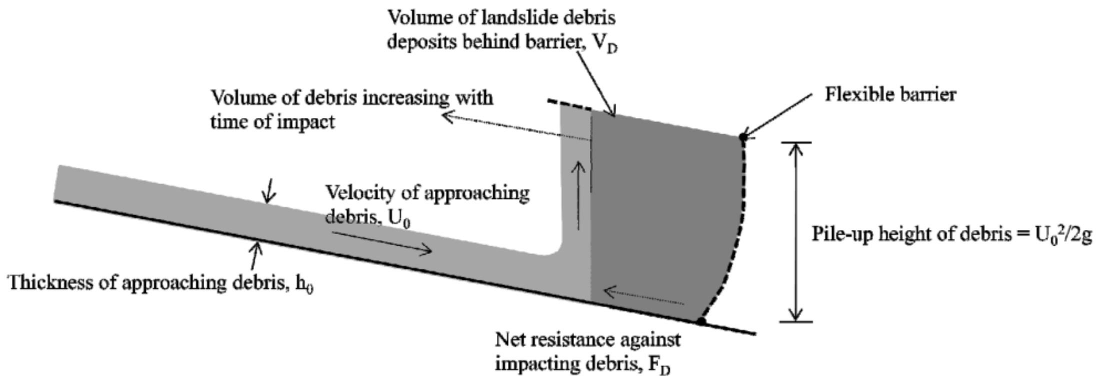
→ Determine the design energy requirement of the flexible barrier i.e. "E"

Step 1 – Debris Mobility Assessment

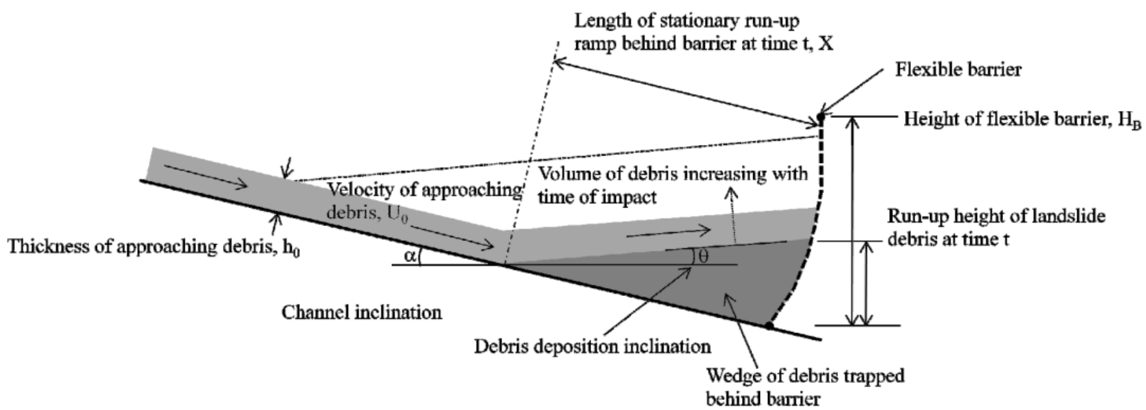


Step 2 – Pile-up and run-up mechanisms (GEO Report 309)

- The energy required to be absorbed by the flexible barrier is calculated based on the limiting deposition processes of landslide debris



(a) Pile-up mechanism



(b) Run-up mechanism

Note: there are some conditions under which the two mechanisms cannot be adopted
e.g. when slope angle ≥ interface friction angle at base of debris plug, E_p *is not applicable*

Step 3 – Upper bound energy requirement

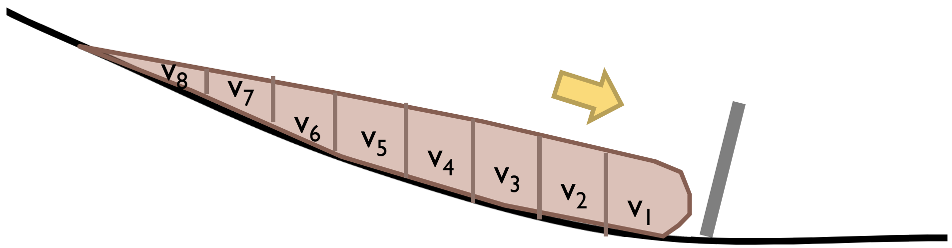
- Instead of taking the upper bound as $E = \frac{1}{2} m_{total} v_{max}^2$, Ek1 and Ek2 are defined:

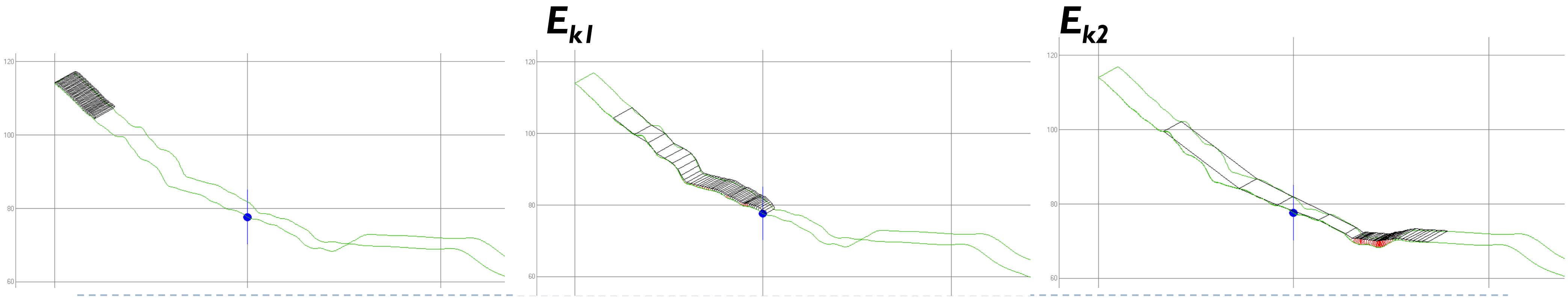
<u>Step 3</u>

Calculate kinetic energy of the entire landslide debris mass (E_k)

$$E_k = \max(E_{k1}, E_{k2})$$

E_{k1} = kinetic energy of landslide debris when the debris front reaches the barrier location
E_{k2} = kinetic energy of landslide debris that travelled beyond the barrier location





Determine Energy Dissipation Capacity "EDC"

- Key design consideration:

Energy Dissipation Capacity (EDC) of barrier
> Energy loading (E) of debris flow

- **EDC** can be established based on
  - **structural analysis (Kwan & Cheung, 2012)** **OR**
  - **field testing (TGN 37)**

> When the energy approach is adopted in analytical design of a flexible barrier, the energy capacity of a barrier established by full-scale rockfall (or other single-mass) tests should be scaled down to cater for the possibility of reduced energy capacity in the case of resisting landslide debris. Until better information becomes available, a scaling factor of not exceeding 75% should be adopted for designing a flexible barrier to mitigate landslide hazards from all types of catchments (i.e. CD, TD and OH).

  - *e.g. EDC of a certified proprietary rockfall barrier rated at 2000 kJ = 2000 * 0.75 = 1500 kJ.*

Force Approach

Barrier Configuration

- Structural form vs site setting
- Structural capacity & retention capacity

Design Loading Scenarios

- Sequential applications of dynamic & static loadings

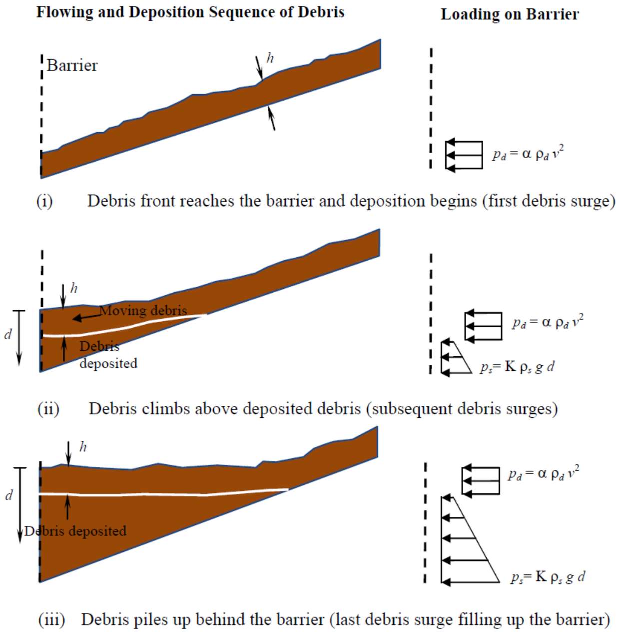
Debris-resisting Capacity

- Modelling to account for non-linear load-deformation behavior of barrier

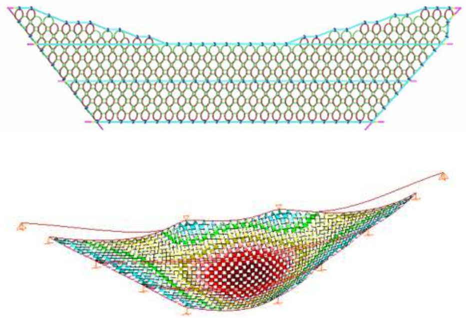
Overall Stability

- Ensure slope stability up to required safety standard

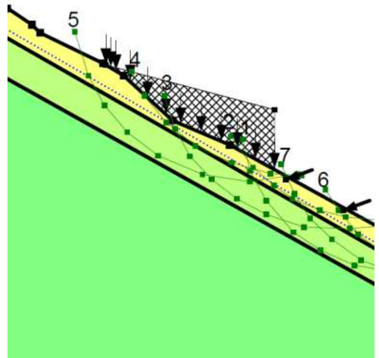
WSL (2009)



Kwan & Cheung (2012)



Chan et al. (2012)



Loadings

- Dynamic impact pressure

$$P_d = \alpha \rho_d v^2$$

velocity

2.0

2,200 kg/m³

- Static earth pressure

$$P_s = K d \rho_s g$$

1.0

deposited depth

2,200 kg/m³

- Overflow drag

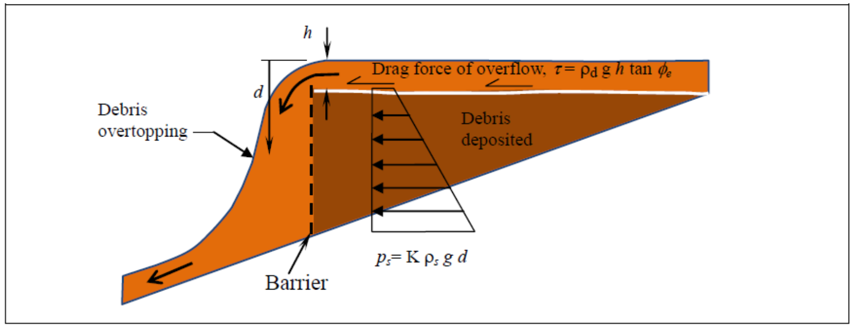


Figure B2 Loading on a Barrier due to Debris Overtopping

The shear stress which will give rise to the drag force should be determined by the equation:

$$\tau = h\, \rho_d\, g \tan\phi_e \quad \text{(B.3)}$$

where h = thickness of debris surge

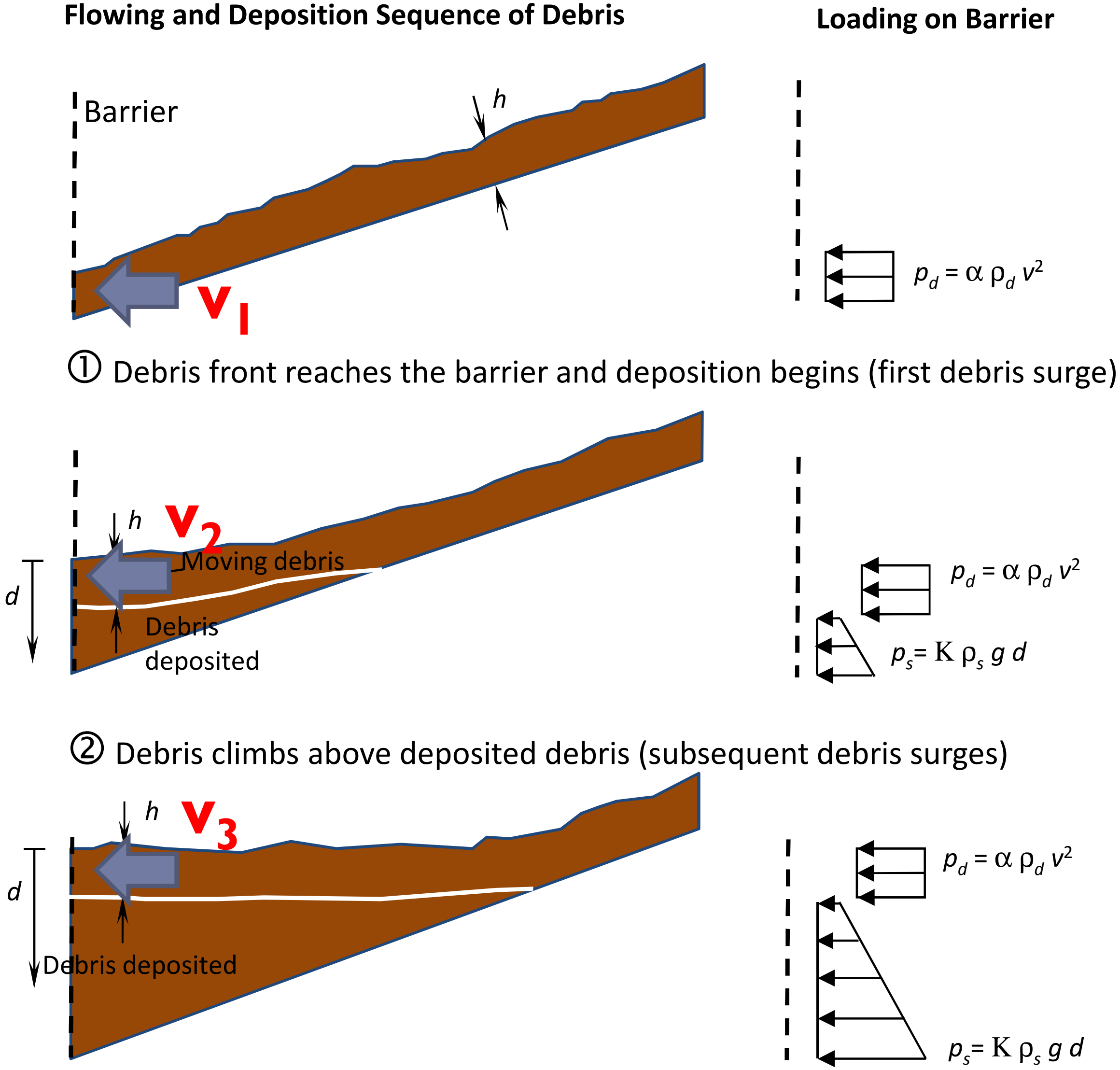
$\tan\phi_e$ = equivalent coefficient of friction at the interface of the overtopping debris surge and the deposited debris and should be taken as $\tan\phi + v^2/(h\xi)$ where v is velocity of overflow, ϕ and ξ are the apparent friction angle and turbulence coefficient adopted in the debris mobility analysis respectively (the second term, $v^2/(h\xi)$, can be dropped when frictional rheological model is used)

- Boulders

(e) Where boulders with diameter greater than 2 m (or with volume exceeding a 2 m diameter sphere) in the debris flow are anticipated, suitable independent measures (e.g. baffles, debris-straining structures or in-situ boulder stabilisation) should be provided to reduce the impact of boulders on the flexible barrier.

Kwan & Cheung (2012)

Debris impact scenario

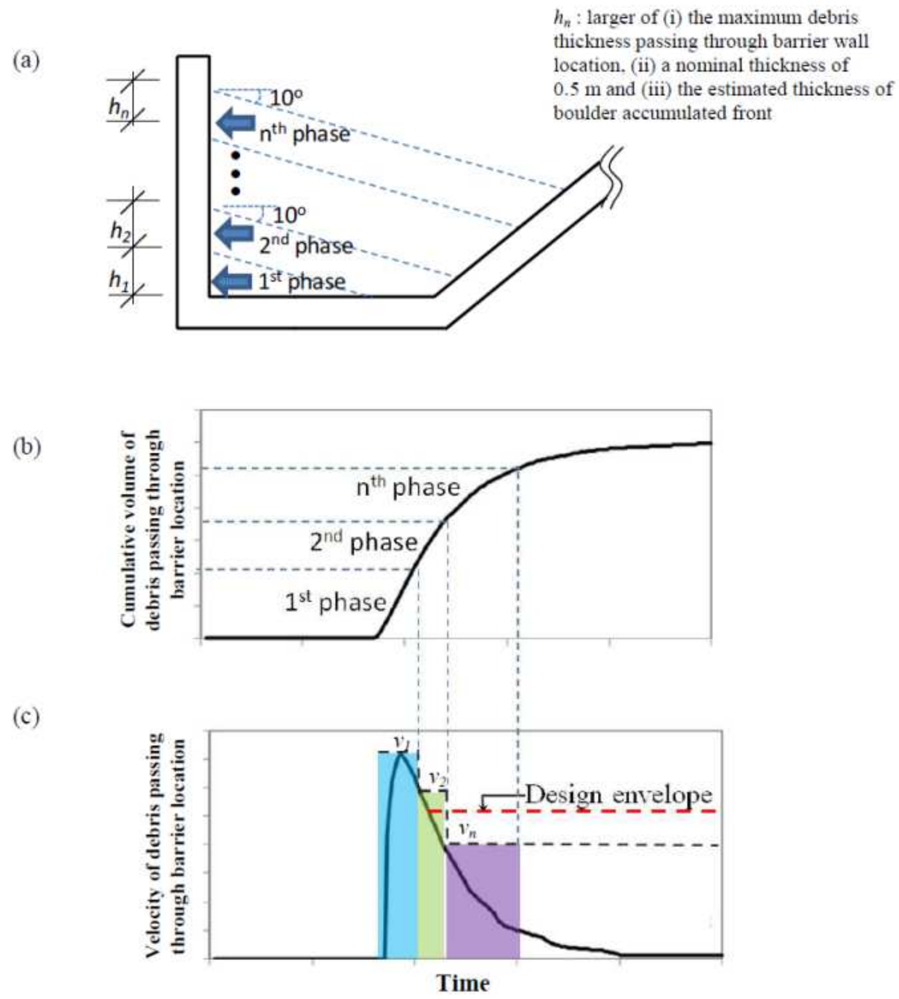


① Debris front reaches the barrier and deposition begins (first debris surge)

② Debris climbs above deposited debris (subsequent debris surges)

③ Debris piles up behind the barrier (last debris surge filling up the barrier)

$v_1 > v_2 > v_3$



v_n = design impact velocity of the n^{th} phase ≮ 0.7 maximum debris velocity of the hydrograph

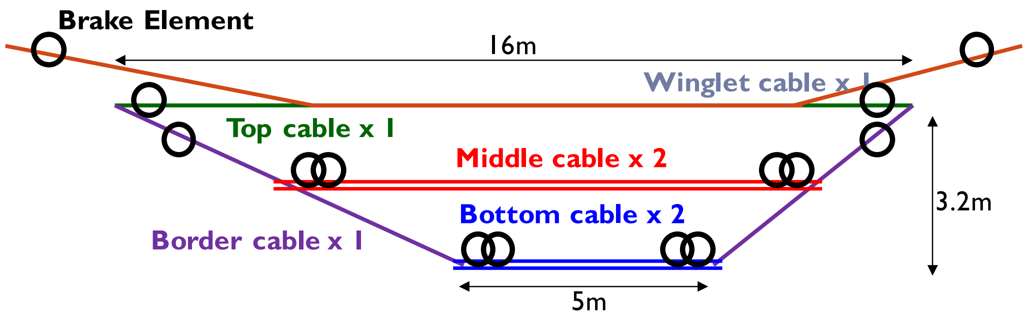
Kwan & Cheung (2012)

TGN44

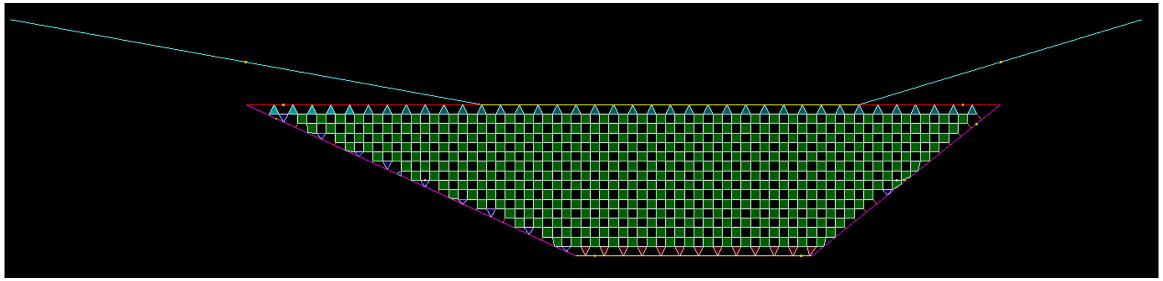
Barrier Configuring & Analysis

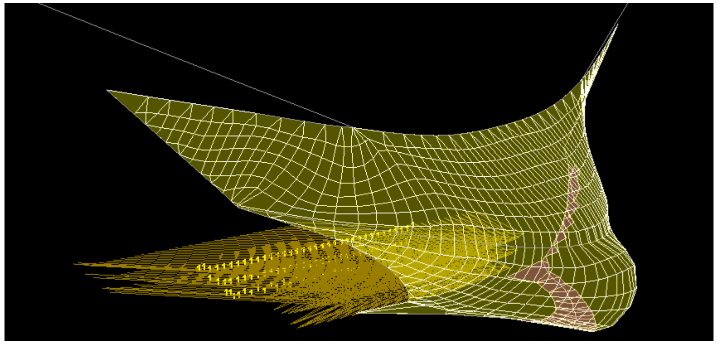
Site Setting

Barrier Configuration



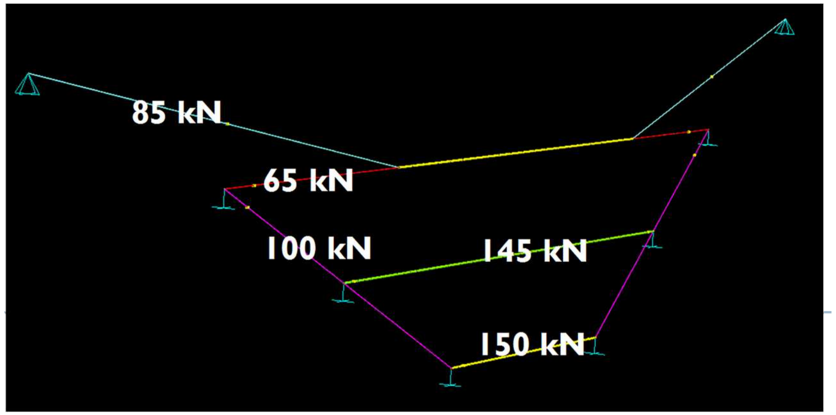
Structural Analysis





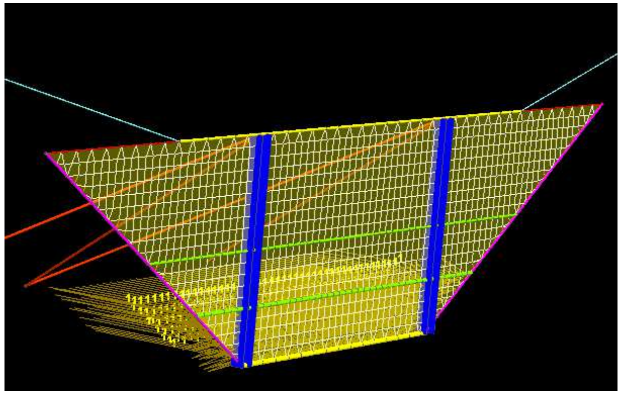
Design & Detailing

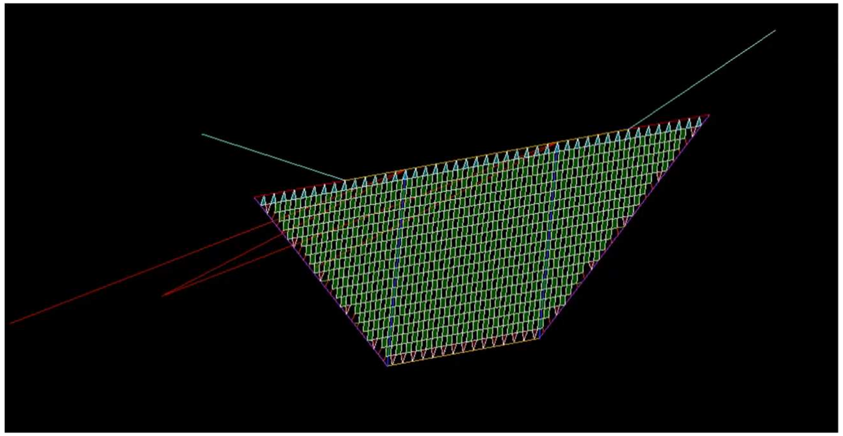
e.g. obtain maximum cable force



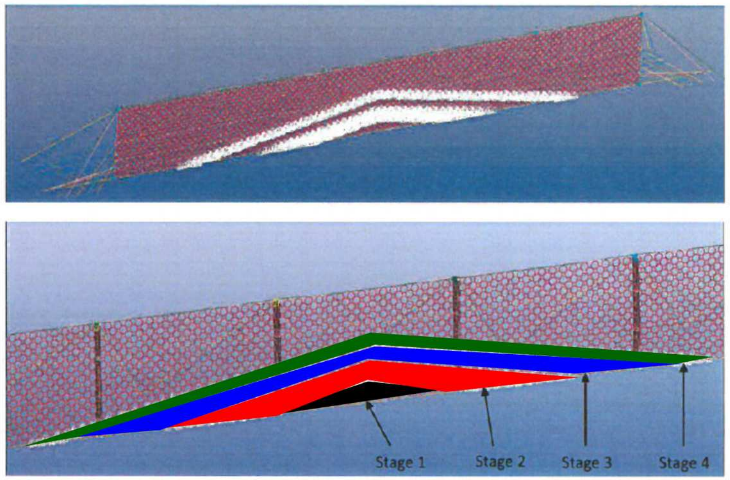
Numerical Programs

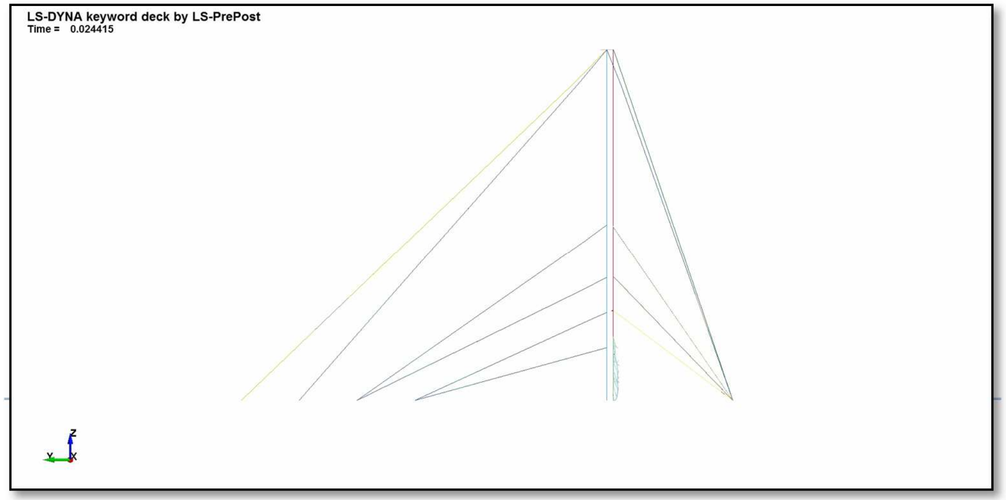
- Models that take into account the non-linear material behavior of flexible barriers under sequential loadings
- e.g. NIDA-MNN (Chan et al. 2012)





- e.g. LS-DYNA (Ng et al., 2012)

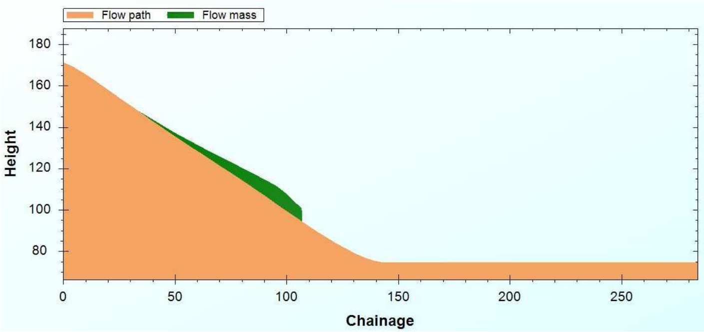




Coupled Analysis

- Force approach is essentially a decoupled analysis

Debris mobility modelling



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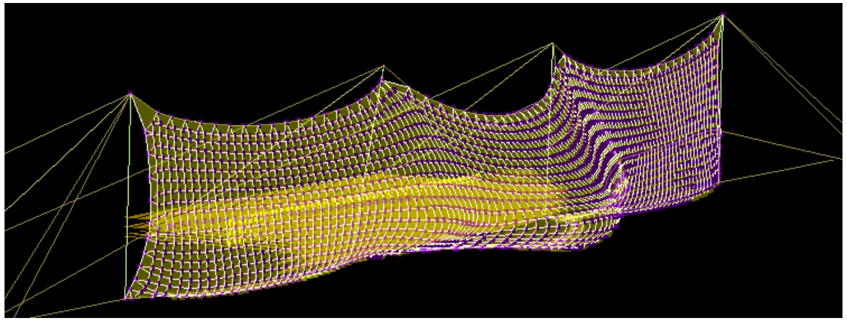
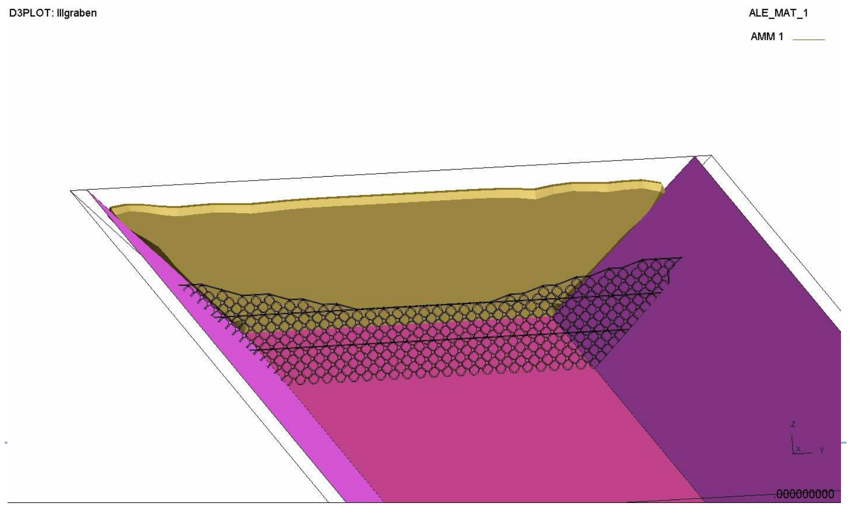
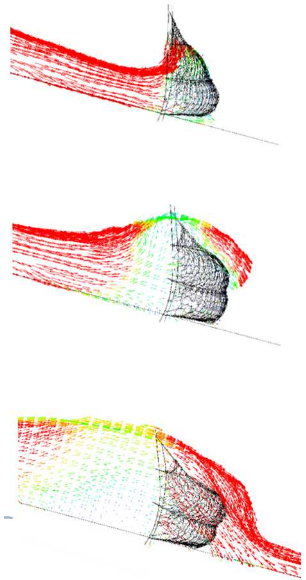
Structural response of barrier



- Coupled analysis explicitly consider the debris-barrier interaction





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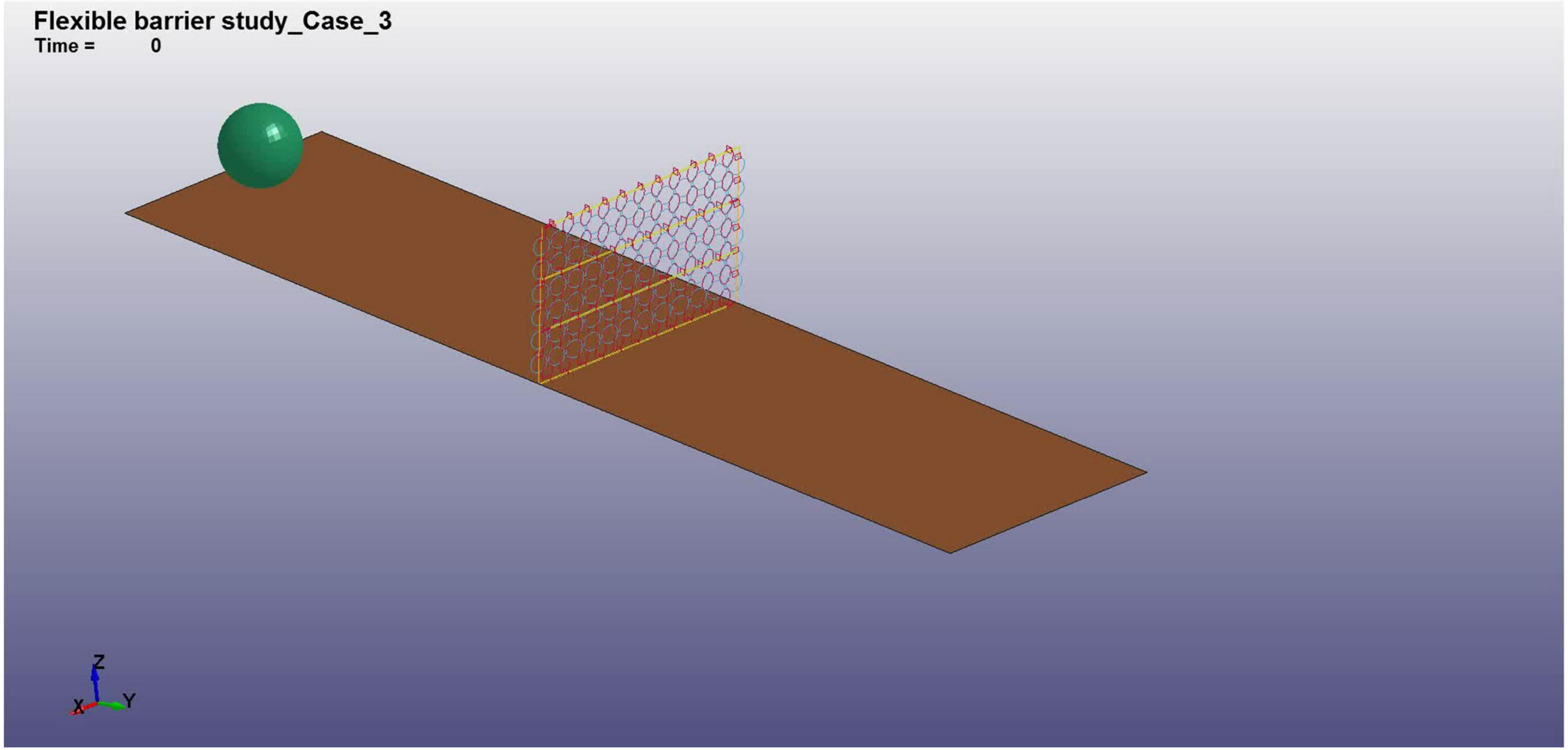
Thank You

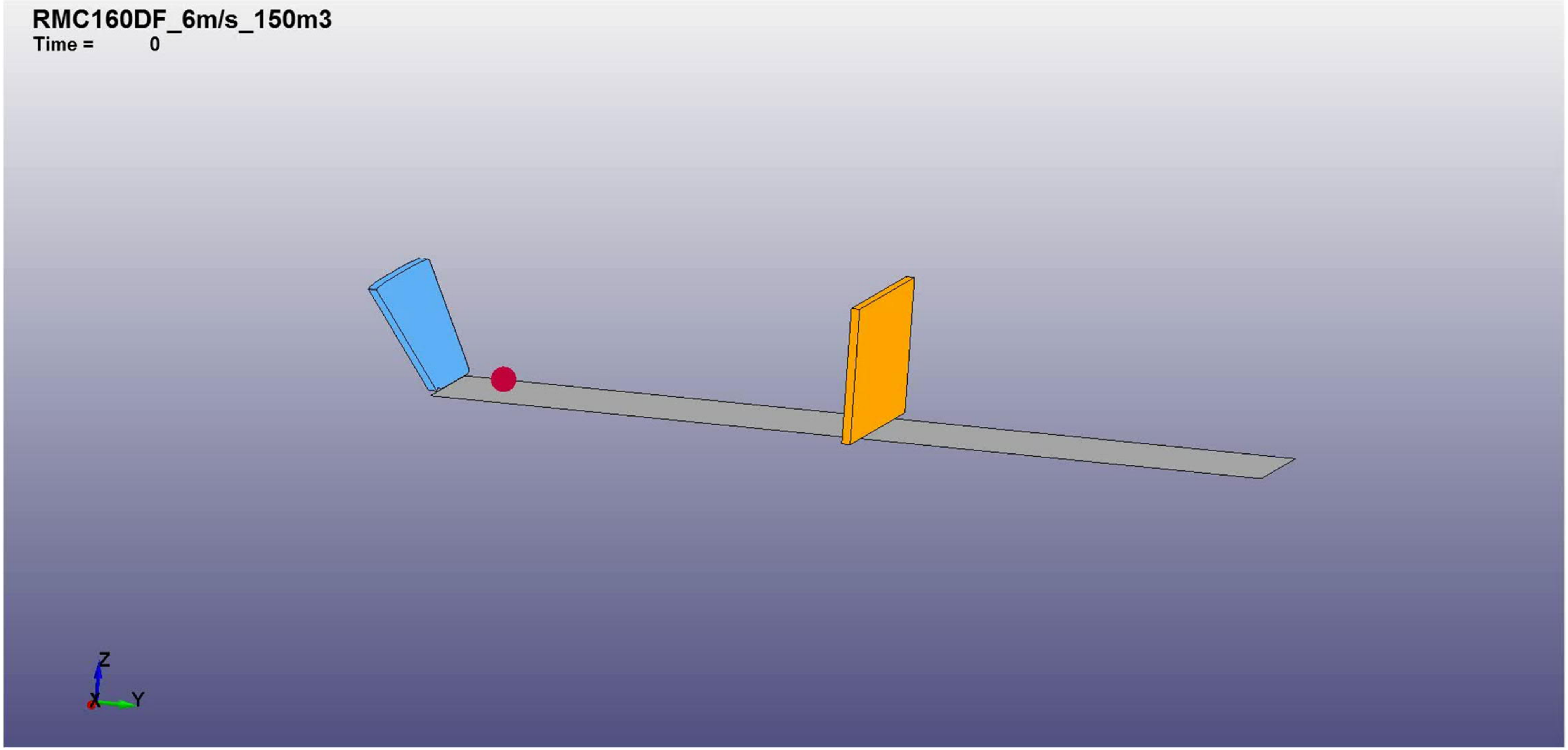
Introduction of LS-DYNA

Workshop on Numerical Modelling for Design of Flexible Debris-resisting Barriers

16 Apr 2019


Flexible barrier study_Case_3
Time = 0
Z
X
Y

Video - debris flow impacting a rigid barrier



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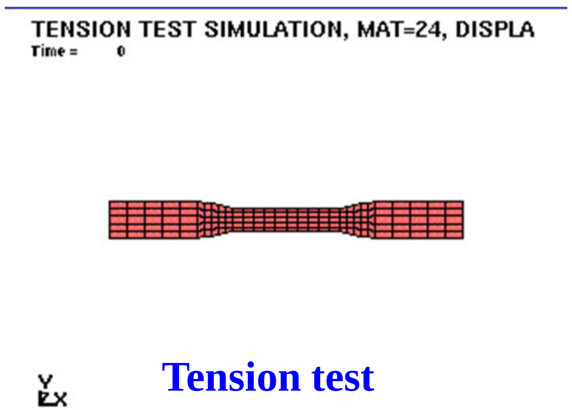
Outline

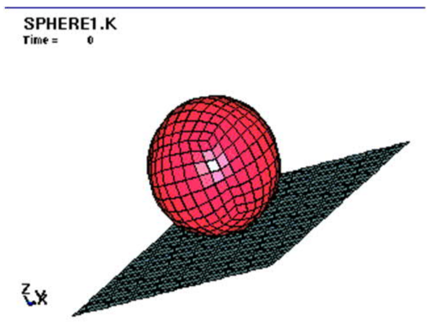
- Background of LS-DYNA
- Basics of a LS-DYNA model
- General modelling guidelines
  - Element type and formulation
  - Typical material models in modelling flexible barriers & debris
  - Contact modelling
  - Initial and boundary conditions
  - Control parameters Unit system
- Post-Processing guidelines
- Useful references

Background of LS-DYNA

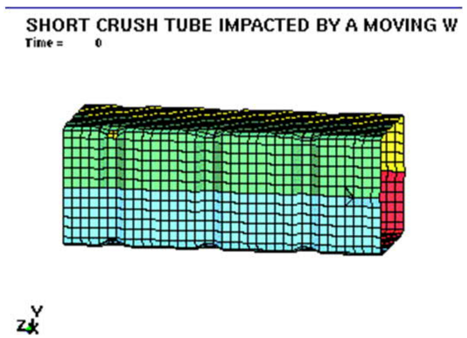
- Developed by Livermore Software Technology Corporation, California, USA
- 2D / 3D, particularly suitable for nonlinear, transient dynamic finite element analysis



Tension test



Boulder hits a elastic plate



Compression of crush tube

Basics of a LS-DYNA model

- A LS-DYNA model: keyword file format – *xxxxx.k*

LS-PrePost

- Geometrical configuration & element generation
- Keyword definition: initial & boundary conditions, time step etc.

LS-PrePost is *Free*

LS-DYNA Program Manager

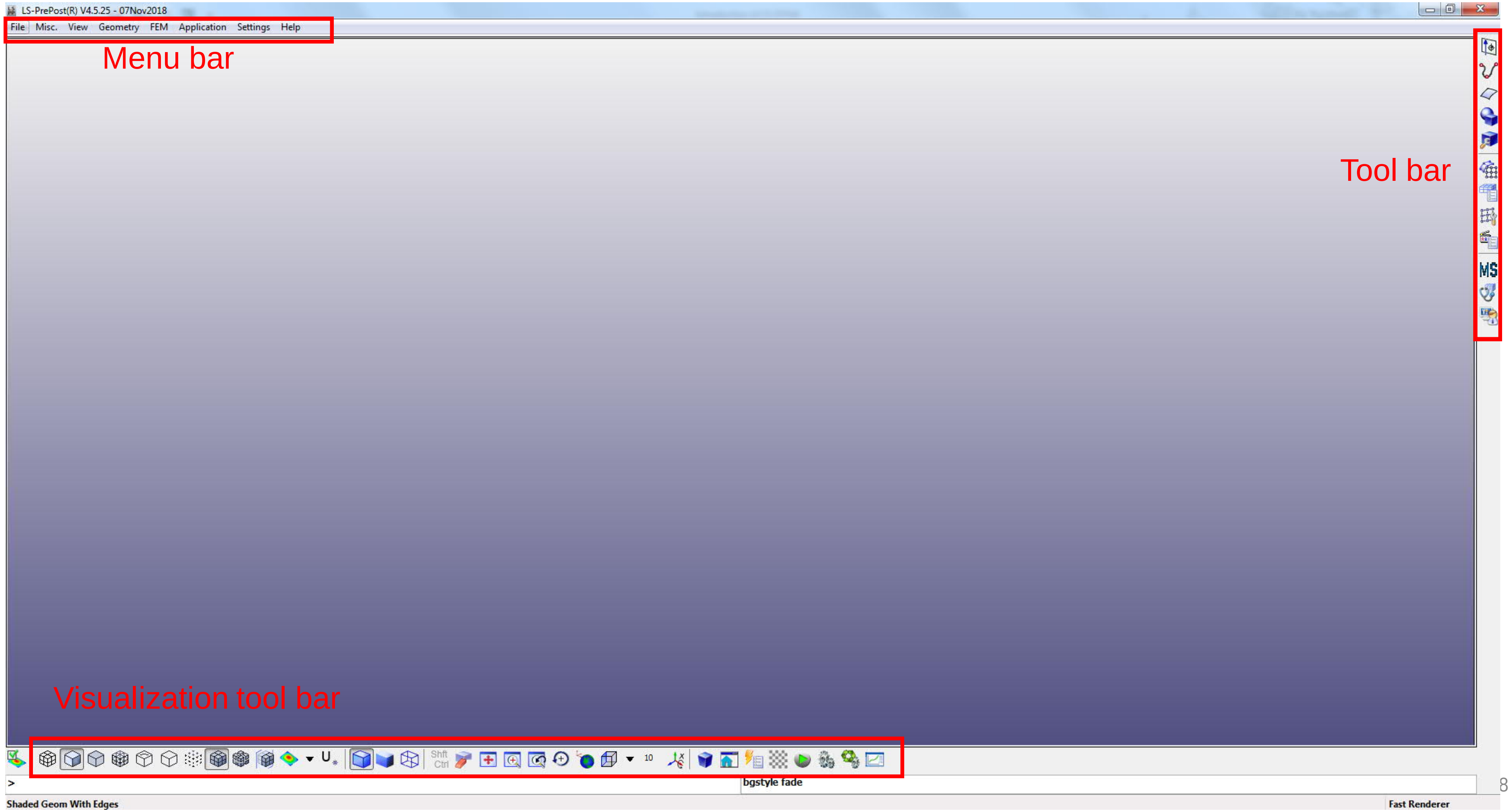
- Solver
- Specify CPU number and memory size to be used

LS-DYNA Program Manager *is licensed*

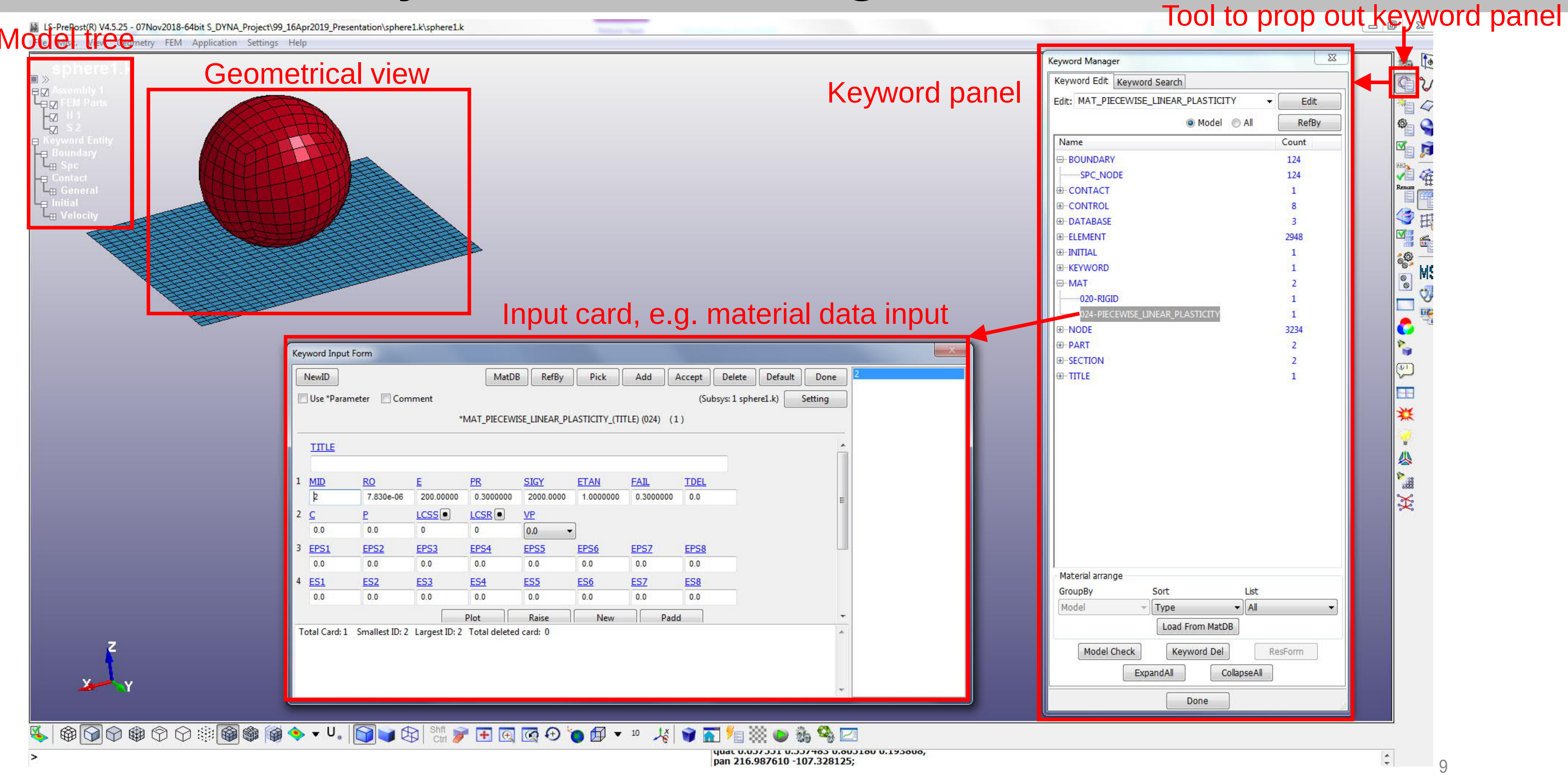
LS-PrePost

- Postprocess: animation, contour…
- Data plot, e.g. cable force – time history plot

LS-PrePost


LS-PrePost(R) V4.5.25 - 07Nov2018
File Misc. View Geometry FEM Application Settings Help
Menu bar
Tool bar
Visualization tool bar
bgstyle fade
Shaded Geom With Edges
Fast Renderer

Generate keyword file using LS-PrePost



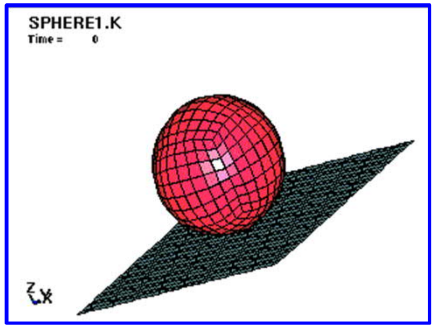
Components of a typical keyword file

Untitled - Notepad

File Edit Format View Help

```
*KEYWORD

*TITLE
sphere1.k
*NODE
$

*ELEMENT_SOLID
$

*SECTION_SOLID
         1         0
*SECTION_SHELL
         2         0 0.0000000 0.0000000 0.0000000 0.0000000         0
 2.5000000 2.5000000 2.5000000 2.5000000 0.0000000

*MAT_PIECEWISE_LINEAR_PLASTICITY
$      mid        ro         e        pr      sigy      etan   faileps
         2 7.83000-6 200.00000 0.3000000 2000.0000 1.0000000 0.3000000 0.0000000
$ e/p and
$                                                              .0000000 0.0000000
*MAT_RIGID
         1 7.83000-6 200.00000 0.3000000 0.0000000 0.0000000 0.0000000

*PART

         1         1         1         0         0         0         0         0
*PART

         2         2         2         0         0         0         0         0

*initial_velocity_generation
1,2,,,,-89

*BOUNDARY_SPC_NODE
$
```

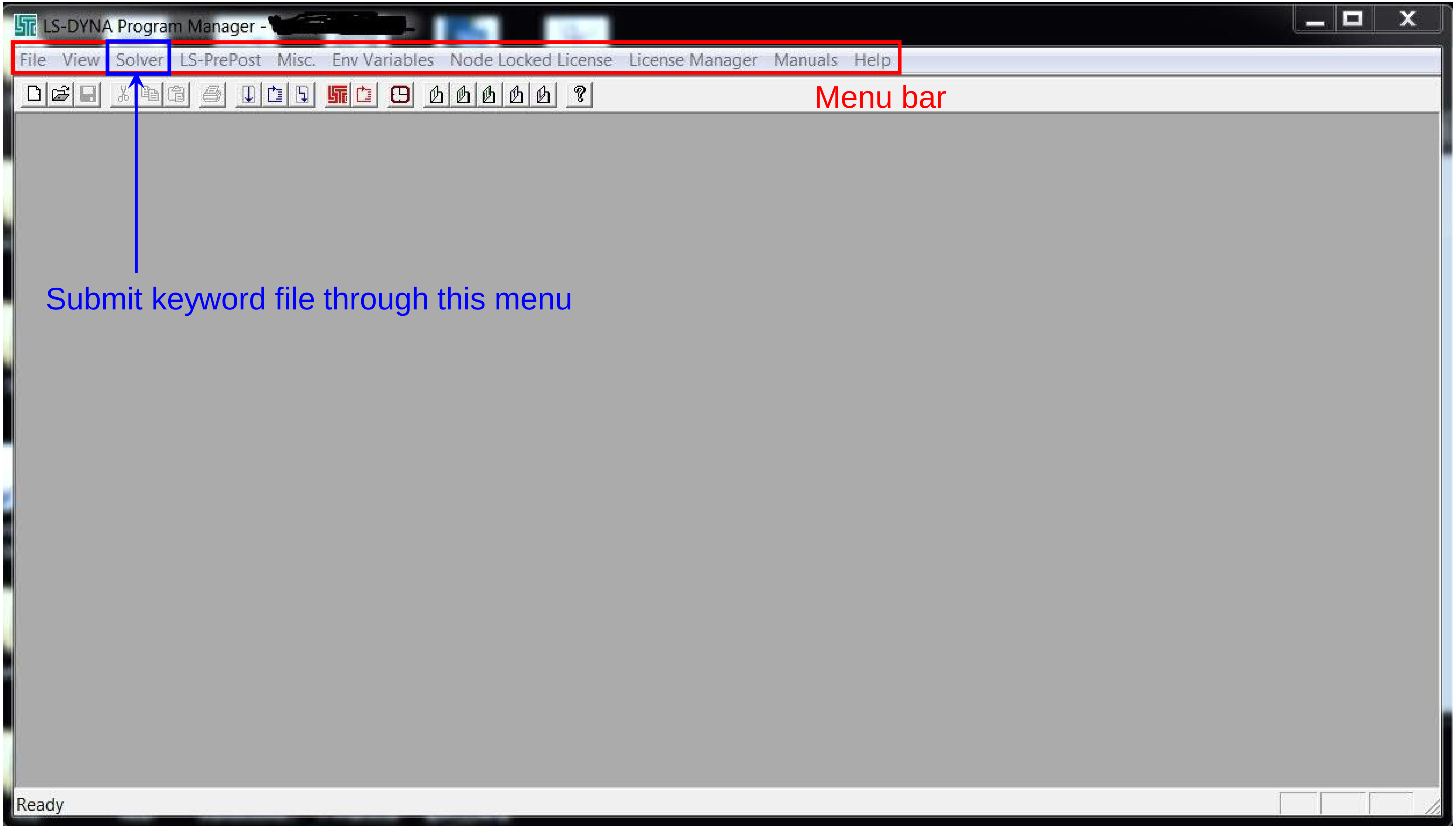
- *NODE: Geometrical information: coordination of each node
- *ELEMENT_SOLID: Element information: which nodes form a specific type of element
- *SECTION_SOLID / *SECTION_SHELL: Section information: such as shell, solid, beam etc.
- *MAT_PIECEWISE_LINEAR_PLASTICITY / *MAT_RIGID: Material constitutive model, e.g. soil, steel
- *PART: Which section, material etc. form which part
- *initial_velocity_generation / *BOUNDARY_SPC_NODE: Define initial & boundary conditions




```
*contact_surface_to_surface
1,2,3,3
*CONTROL_TERMINATION
 1.0000000         0 0.0000000         0 0.0000000
*CONTROL_TIMESTEP
 0.0000000 0.0000000         0 0.0000000 0.0000000         0         0         0
*CONTROL_SHELL
 0.0000000         0         0         0         0         0         0
*CONTROL_DAMPING
         0 0.0000000 0.0000000 0.0000000 0.0000000         0 0.0000000         0
*CONTROL_CONTACT
 0.0000000 0.0000000         0         0         0         0         0
         0         0         0         0 0.0000000         0         0         0
*CONTROL_OUTPUT
         0         0         0         0 0.0000000         0         0
*CONTROL_ENERGY
         1         2         1         1

*DATABASE_BINARY_D3PLOT
 0.1000000         0
*DATABASE_BINARY_D3THDT
 10.000000
*DATABASE_EXTENT_BINARY
         0         0         0         0         0         0         0         0
         0         0         0         0         0         0

*END
```

- *contact_surface_to_surface: Define how two parts interact
- *CONTROL_...: Define when model stops running, time step etc.
- *DATABASE_...: Define which information to be output in the result file

LS-DYNA Program Manager



Computation status

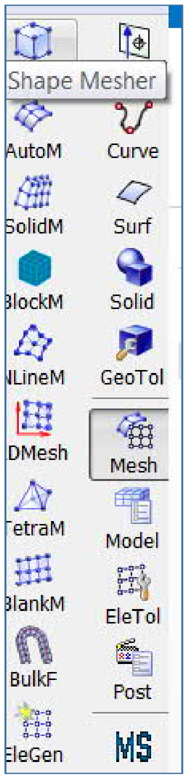
```
total energy / initial energy..   6.39712E-01
energy ratio w/o eroded energy.   6.39712E-01
global x velocity.............    0.00000E+00
global y velocity.............    3.09588E-01
global z velocity.............   -8.41055E-02

number of shell elements that
reached the minimum time step..    0
      1 t 0.0000E+00 dt 4.61E-06 flush i/o buffers
      1 t 0.0000E+00 dt 4.61E-06 write d3plot file
Summary of edge-to-edge contact interface # =            1
  number of warnings for interpenetration    =         1998
  number of warnings for segment deletion    =            0
cpu time per zone cycle............          0 nanoseconds
average cpu time per zone cycle....       2852 nanoseconds
average clock time per zone cycle..       2852 nanoseconds

estimated total cpu time          =    295733 sec (      82 hrs
estimated cpu time to complete    =    295727 sec (      82 hrs
estimated total clock time        =    295733 sec (      82 hrs
estimated clock time to complete  =    295727 sec (      82 hrs
```

$B_n=B_{n-1}+(A_n- A_{n-1})*C_n$, n – row number

A (cycle) B (current time) C (Time step) Termination time

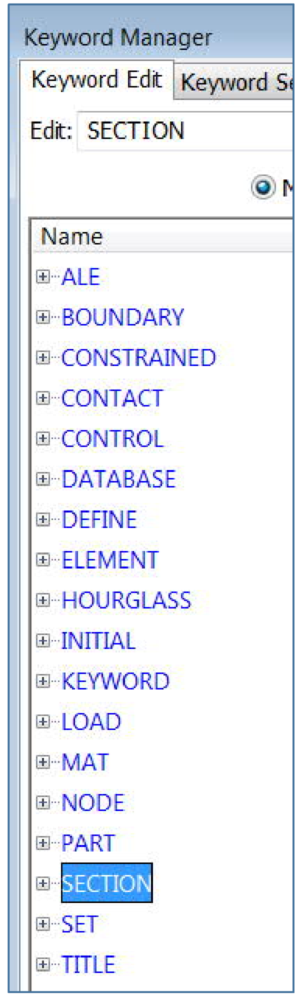
```
termination time                           = 5.000E+00
  5000 t 2.3049E-02 dt 4.61E-06 flush i/o buffers
 10000 t 4.6093E-02 dt 4.61E-06 flush i/o buffers
 15000 t 6.9127E-02 dt 4.61E-06 flush i/o buffers
 20000 t 9.2149E-02 dt 4.60E-06 flush i/o buffers
 21705 t 9.9997E-02 dt 4.60E-06 write d3plot file
 25000 t 1.1516E-01 dt 4.60E-06 flush i/o buffers
 30000 t 1.3816E-01 dt 4.60E-06 flush i/o buffers
 35000 t 1.6115E-01 dt 4.60E-06 flush i/o buffers
 40000 t 1.8413E-01 dt 4.59E-06 flush i/o buffers
 43454 t 2.0000E-01 dt 4.59E-06 write d3plot file
 45000 t 2.0710E-01 dt 4.59E-06 flush i/o buffers
 50000 t 2.3004E-01 dt 4.58E-06 flush i/o buffers
 55000 t 2.5285E-01 dt 4.54E-06 flush i/o buffers
 60000 t 2.7538E-01 dt 4.46E-06 flush i/o buffers
 65000 t 2.9752E-01 dt 4.39E-06 flush i/o buffers
 65564 t 3.0000E-01 dt 4.38E-06 write d3plot file
 70000 t 3.1933E-01 dt 4.33E-06 flush i/o buffers
```

General modelling guidelines



- For regular shape shell and solid elements, the meshed elements can be generated by "Shape Mesher"
- For irregular shape shell and solid elements, the object should be created first using the point, curve, surface tolls and then using "Auto Mesher" or "Solid Mesher" to generate elements
- For beam element, a curve should be created first and then using the "Element Generation" to generate beam elments

- SECTION-Define the element type (beam, shell, solid)
- MAT-Define the material properties and constitutive model
- PART-Assign the SECTION and MAT information into different modelling elements
- CONTACT-Define the interaction between different parts
- CONSTRAINED-Define the coupling mechanism of Fluid-Structure interaction
- BOUNDARY-Define the boundary conditions
- INITIAL-Define the initial conditions
- LOAD-Define applied load (e.g., gravity)
- CONTROL-Change defaults and activate solution options

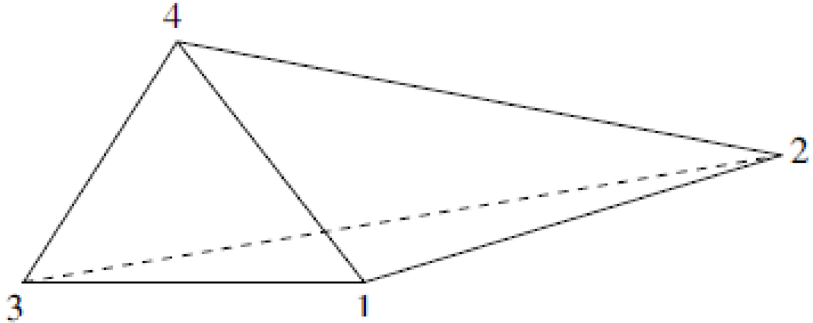


General modelling guidelines

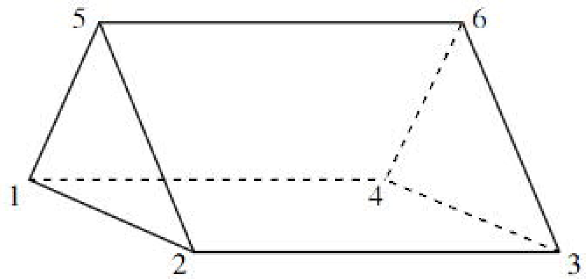
- Element type and formulation
- Material model
- Contact modelling
- Initial and boundary conditions
- Control parameters
- Unit system

Element in LS-DYNA

Solid elements – element shape

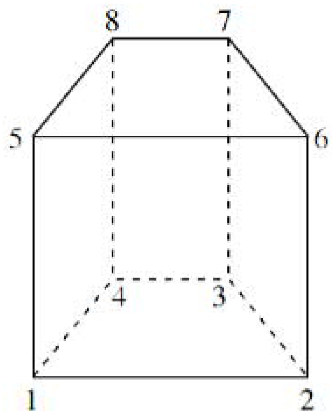


4-node



6-node

In many cases, LS-DYNA automatically
generates the shape based on user defined
element size and model geometry

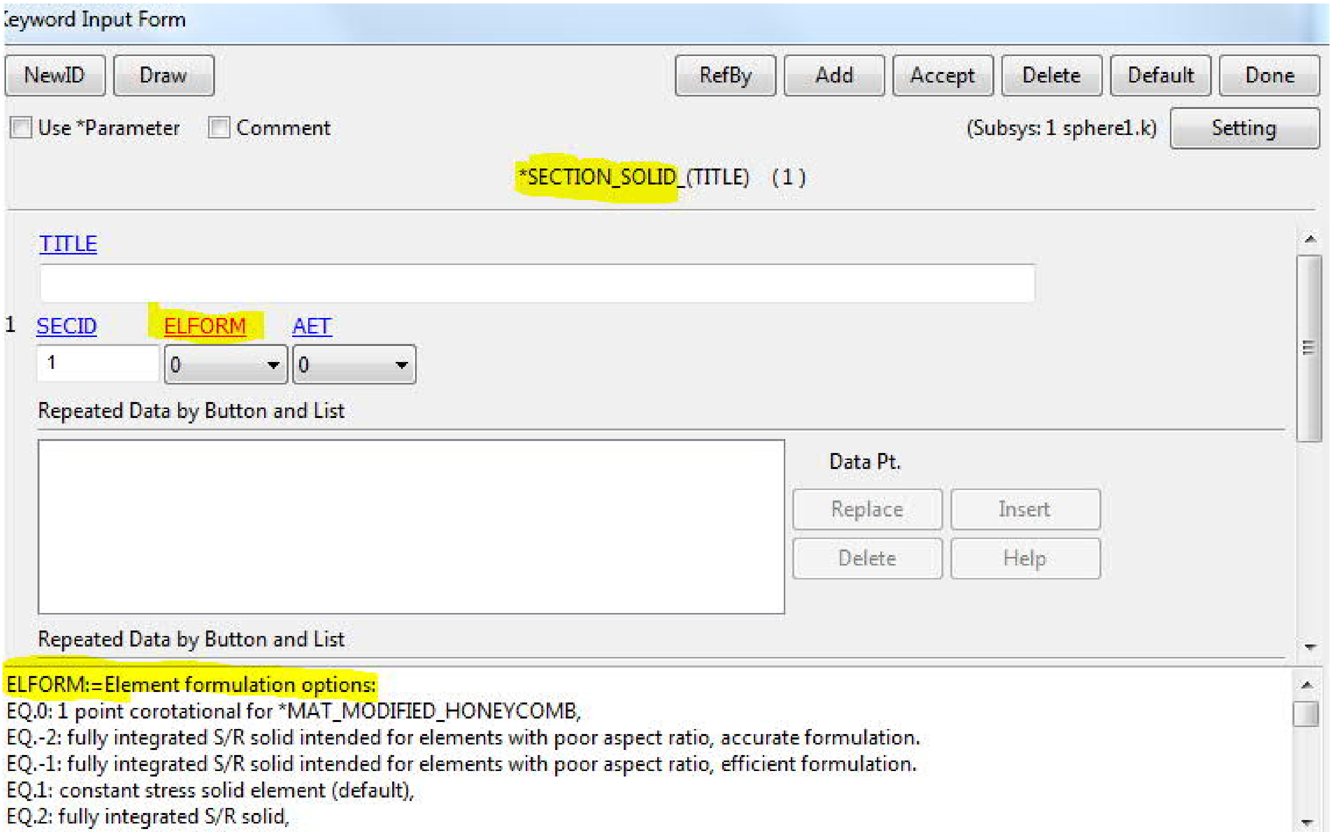


8-node

….

Solid elements – element formulation

- Numerical formulation of that element



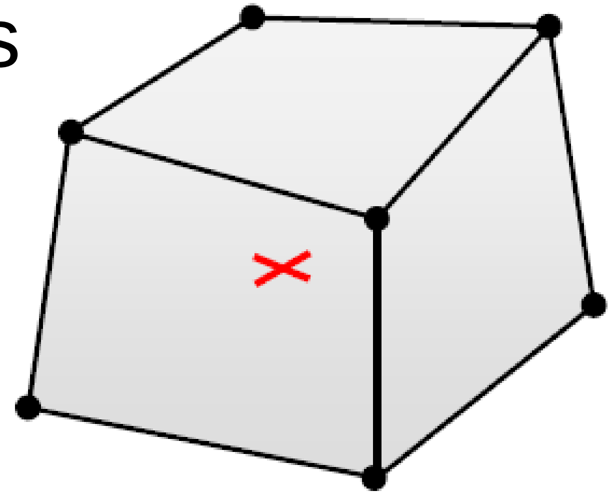
Solid element formulation options

EQ.0: 1 point corotational for *MAT_MODIFIED_HONEYCOMB.
EQ.1: constant stress solid element (default),
EQ.2: fully integrated S/R solid.
EQ.3: fully integrated quadratic 8 node element with nodal rotations,
EQ.4: S/R quadratic tetrahedron element with nodal rotations,
EQ.5: 1 point ALE,
EQ.6: 1 point Eulerian,
EQ.7: 1 point Eulerian ambient,
EQ.8: acoustic,
EQ.9: 1 point corotational for *MAT_MODIFIED_HONEYCOMB
EQ.10: 1 point tetrahedron.
EQ.11: 1 point ALE multi-material element ← **Large deformation, e.g. debris**
EQ.12: 1 point integration with single material and void.
EQ.13: 1 point nodal pressure tetrahedron for bulk forming.
EQ.14: 8 point acoustic
EQ.15: 2 point pentahedron element.
EQ.18: 8 point enhanced strain solid element for linear statics only,
EQ.31: 1 point Eulerian Navier-Stokes
EQ.32: 8 point Eulerian Navier-Stokes

⋮

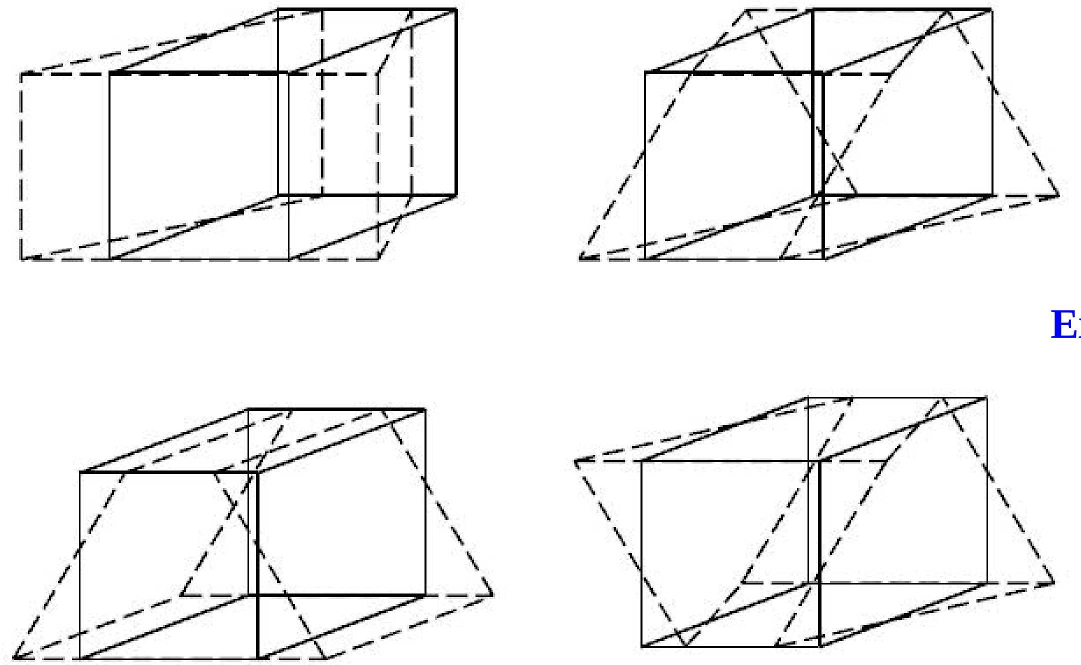
Constant stress solid element (ELFORM=1)

- Under-integrated: only ONE Gaussian point
- Efficient while less accuracy
- Even works for severe deformations
- Needs Hourglass stabilization



Hourglass

- Hourglass (HG) modes are nonphysical, zero-energy modes of deformation that produce zero strain and no stress. Hourglass modes **occur only in under-integrated** (single integration point) solid, shell, and thick shell elements.



Examples of Hourglass modes of solid element

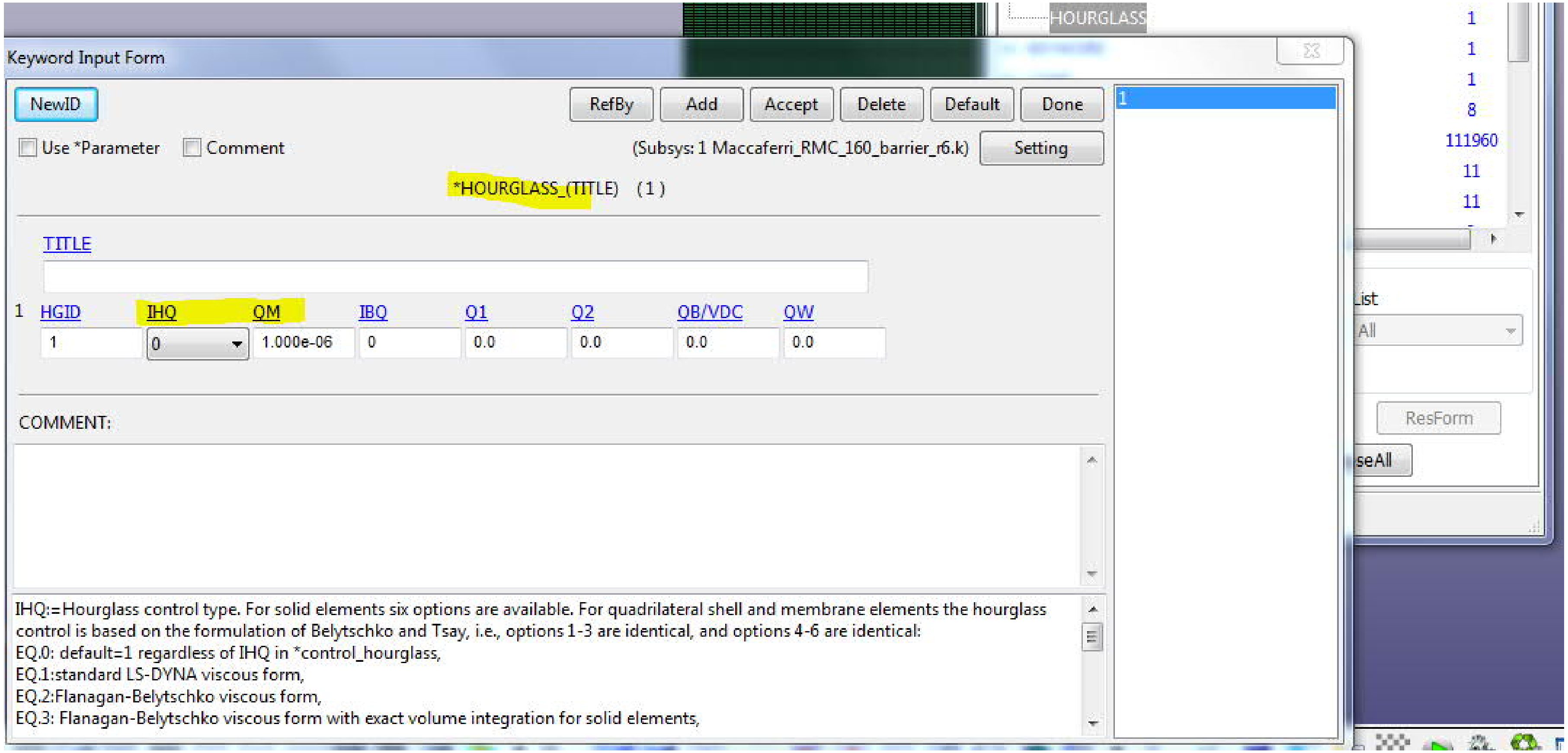
Keywords related to Hourglass control algorithms

- Hourglass can usually be controlled by applying internal forces to resist hourglass modes via Hourglass control algorithms

- *CONTROL_HOURGLASS
  - Sets global hourglass formulation and coefficient
- *HOURGLASS
  - Sets hourglass formulation and coefficient for specific parts *(overrides global setting)*
- *CONTROL_ENERGY
  - Set HGEN to 2 to have hourglass energy calculated **(recommended)**

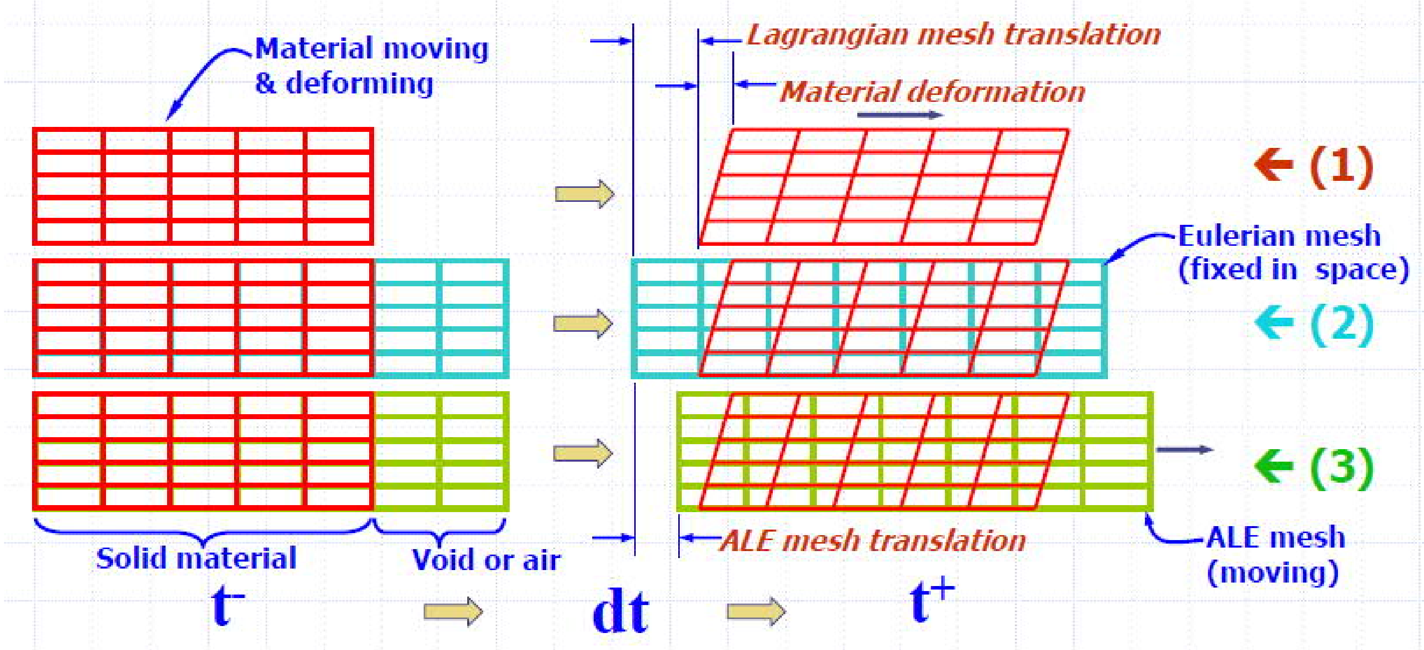
Takeaway recommendation

- Adopt default setting and QM (hourglass coefficient, < 0.15) for flexible barrier and debris interaction problem



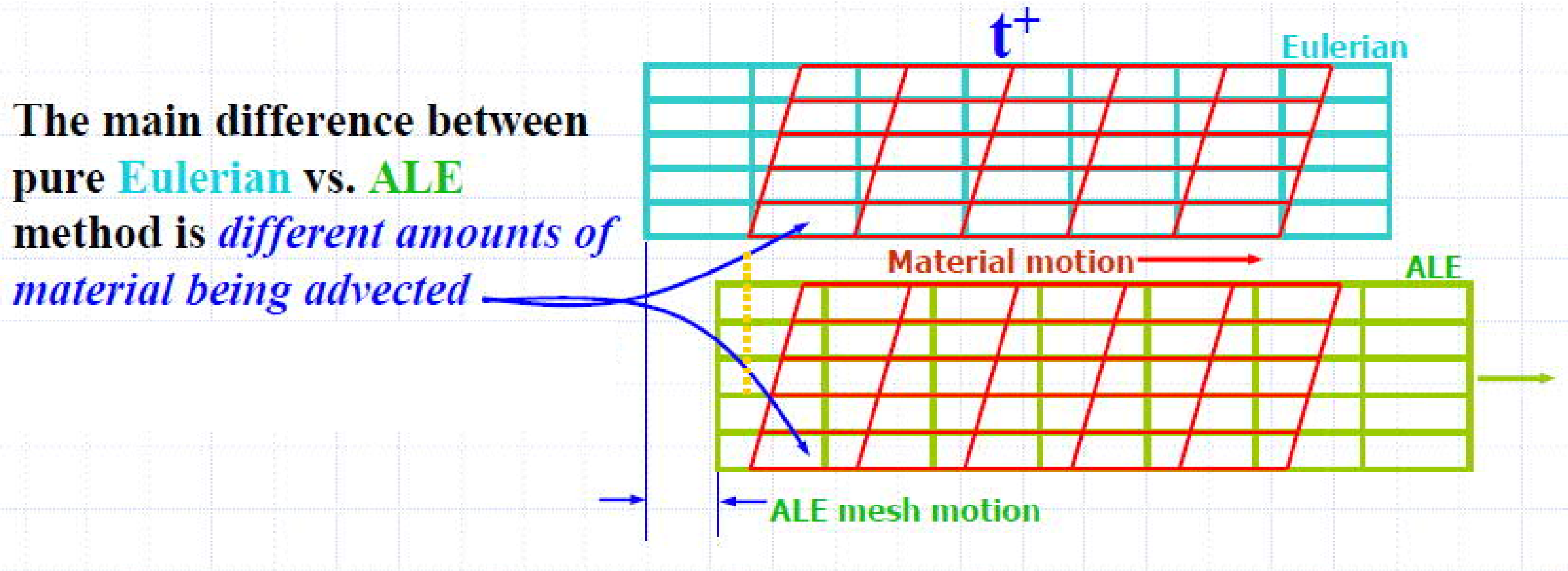
Large deformation modelling – ALE method

	Finite element algorithms adopted in continuum mechanics		
Algorithms	(1) Lagrangian	(2) Eulerian	(3) Arbitrary Lagrangian–Eulerian
Description	Computational mesh moves together with the material continuum	Computational mesh is fixed and the continuum moves with respect to the grid	Both computation mesh and the material continuum can move (but not necessary together)
Example software	PLAXIS, Phase2, SAFE, FLAC, LS-DYNA	LS-DYNA	LS-DYNA

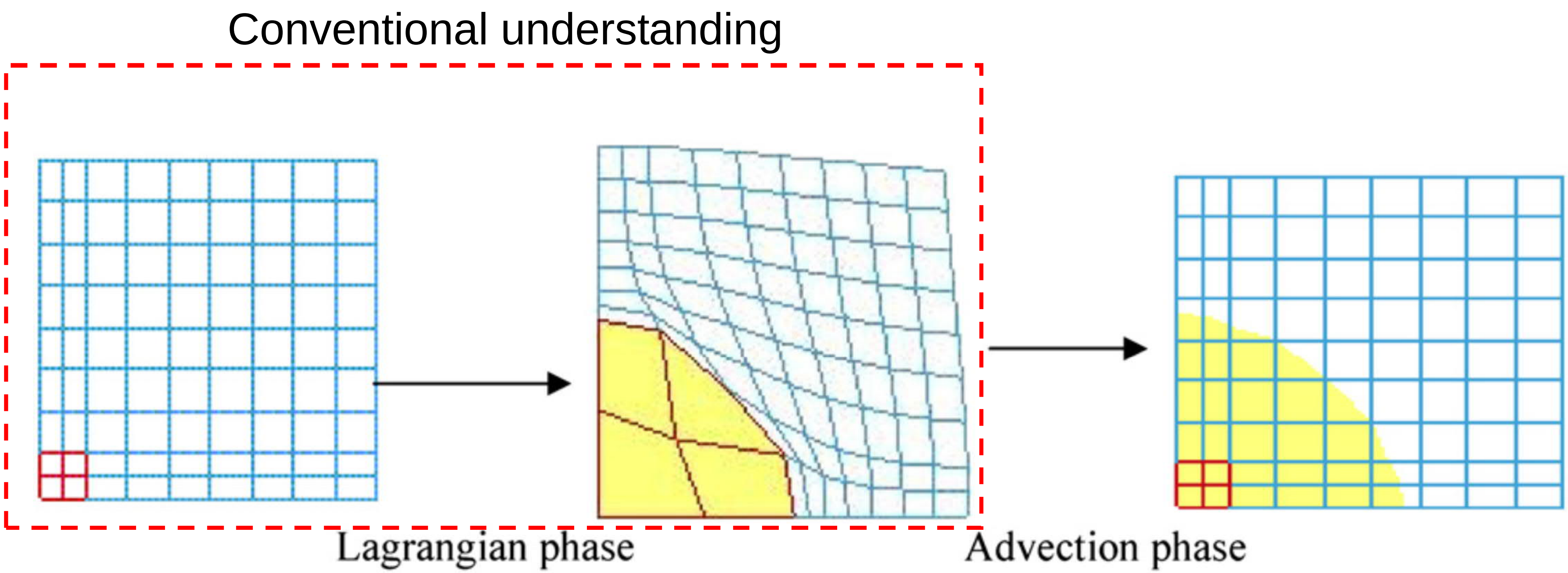


Difference between Eulerian and ALE

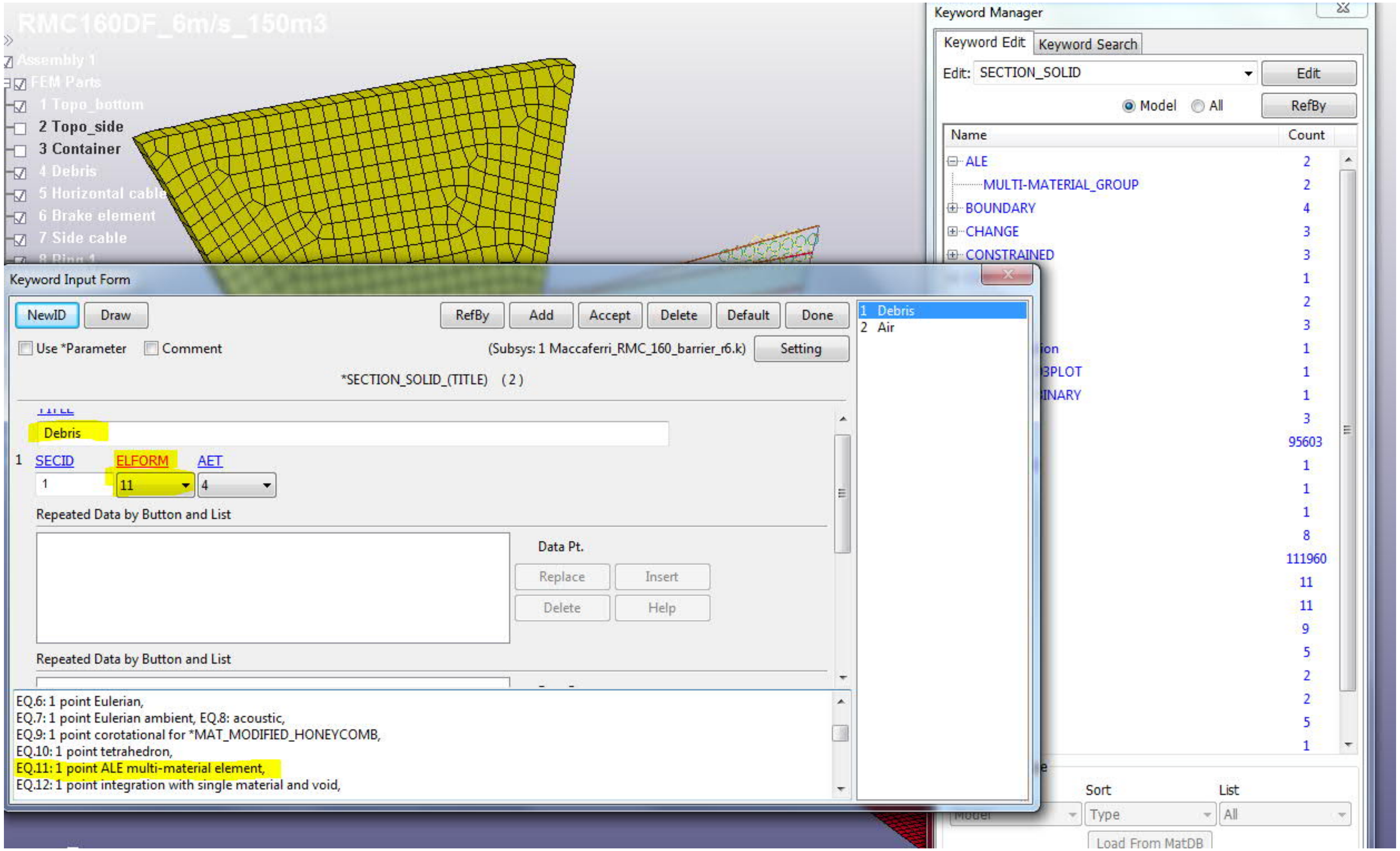
- Eulerian method is a subset of the ALE where the computational mesh stays fixed in space



An illustration

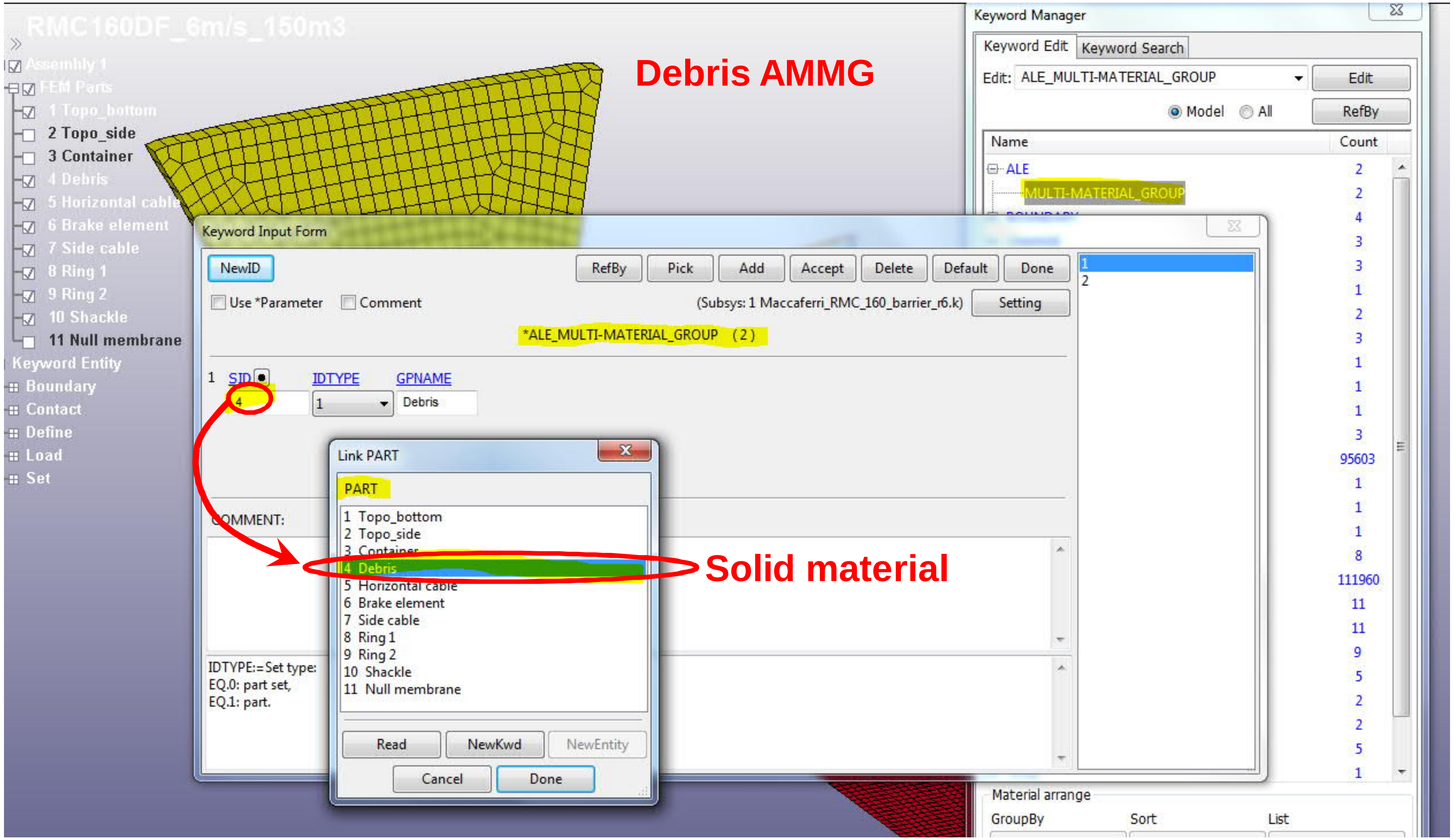


Element formulation for modelling debris

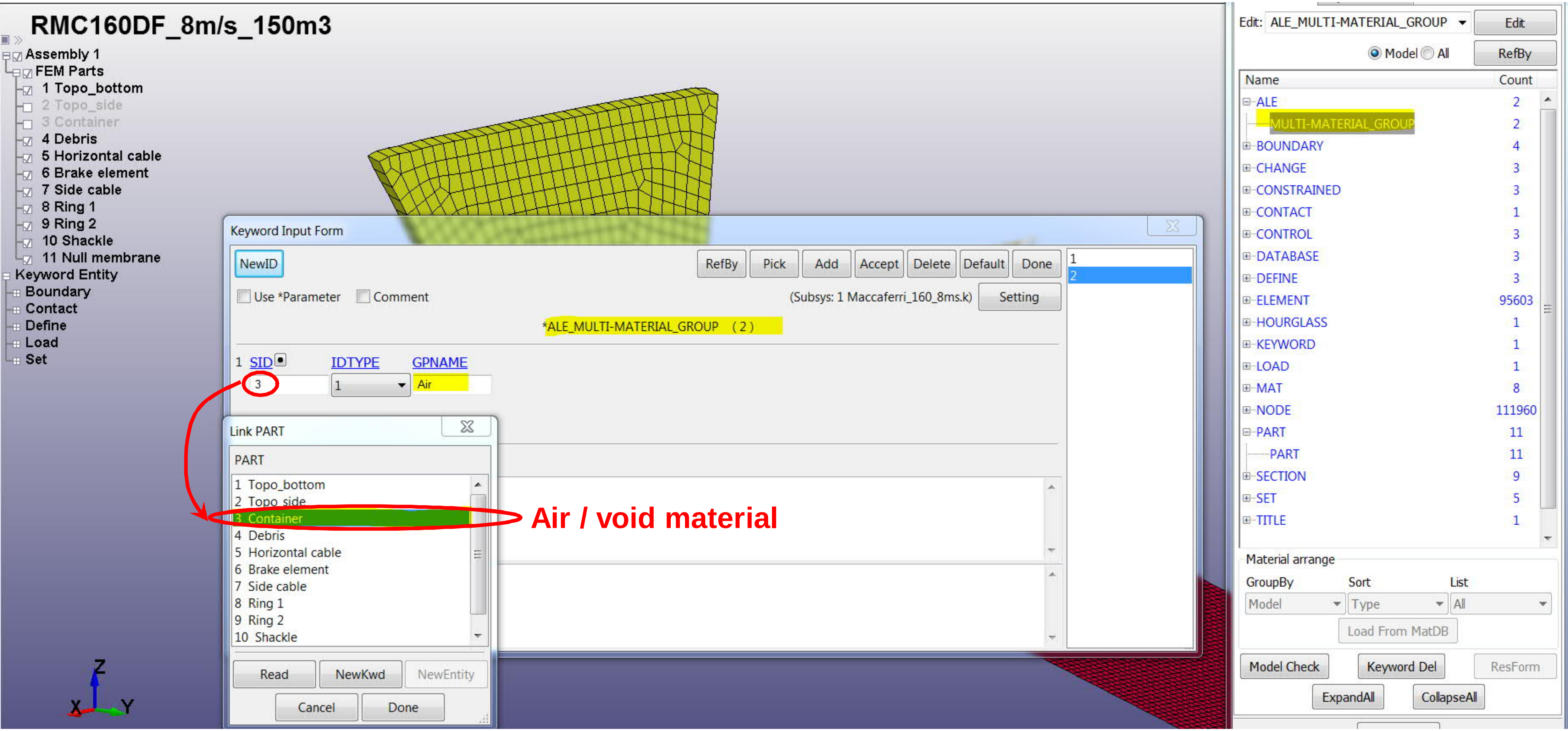


Keyword used together with ELFORM=11

- *ALE_MULTI-MATERIAL_GROUP (AMMG)

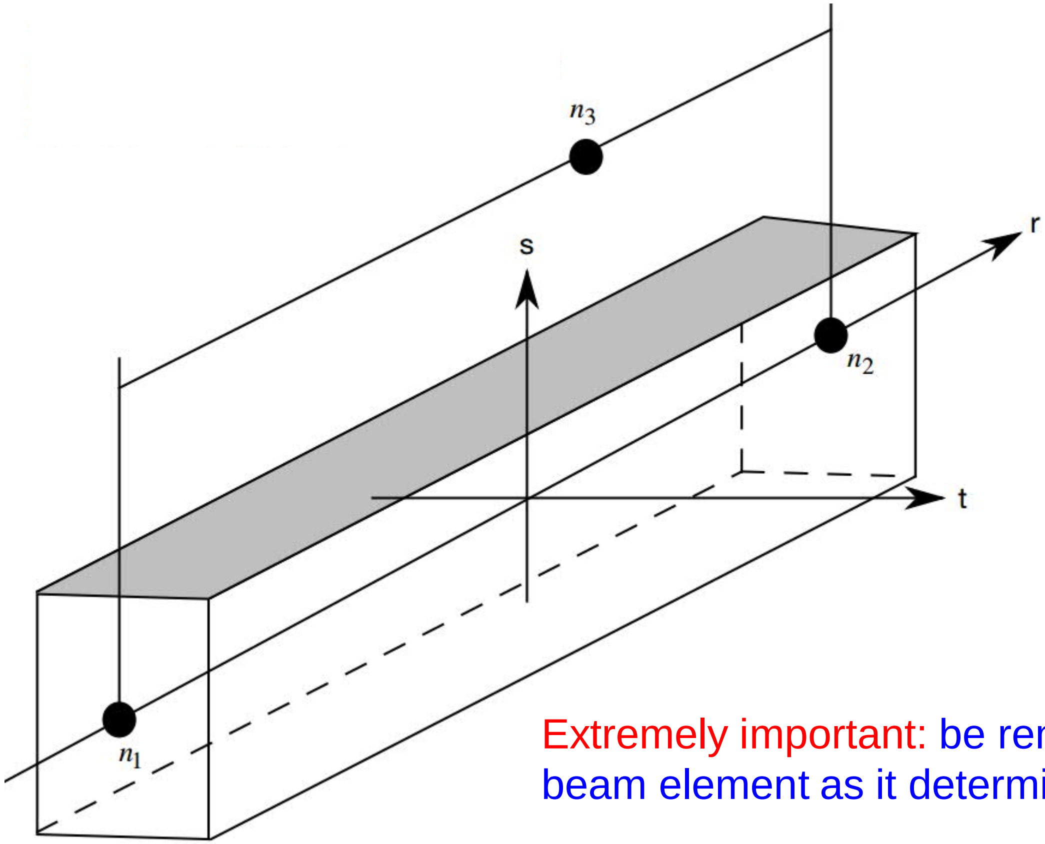


Air / void AMMG



Beam elements

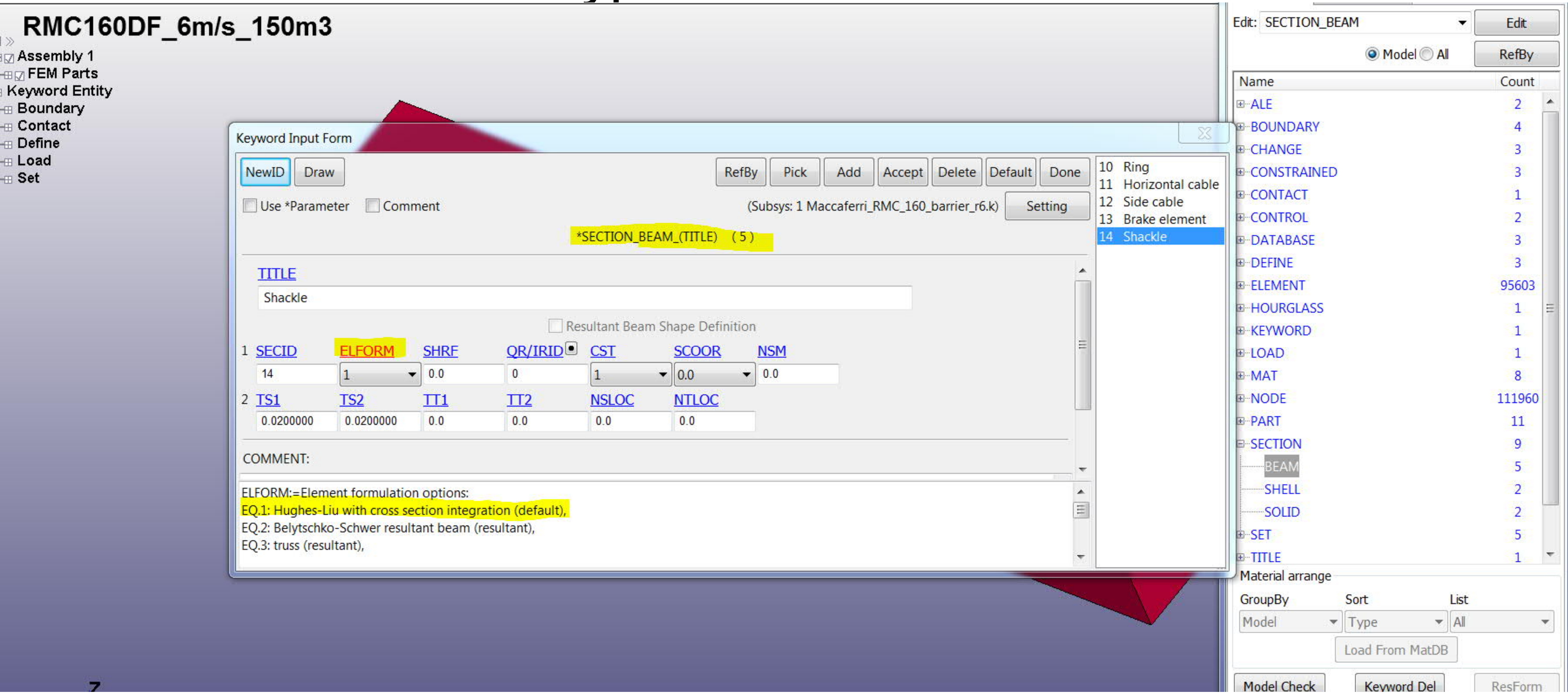
- All structures components of a flexible barrier are modelled by beam elements



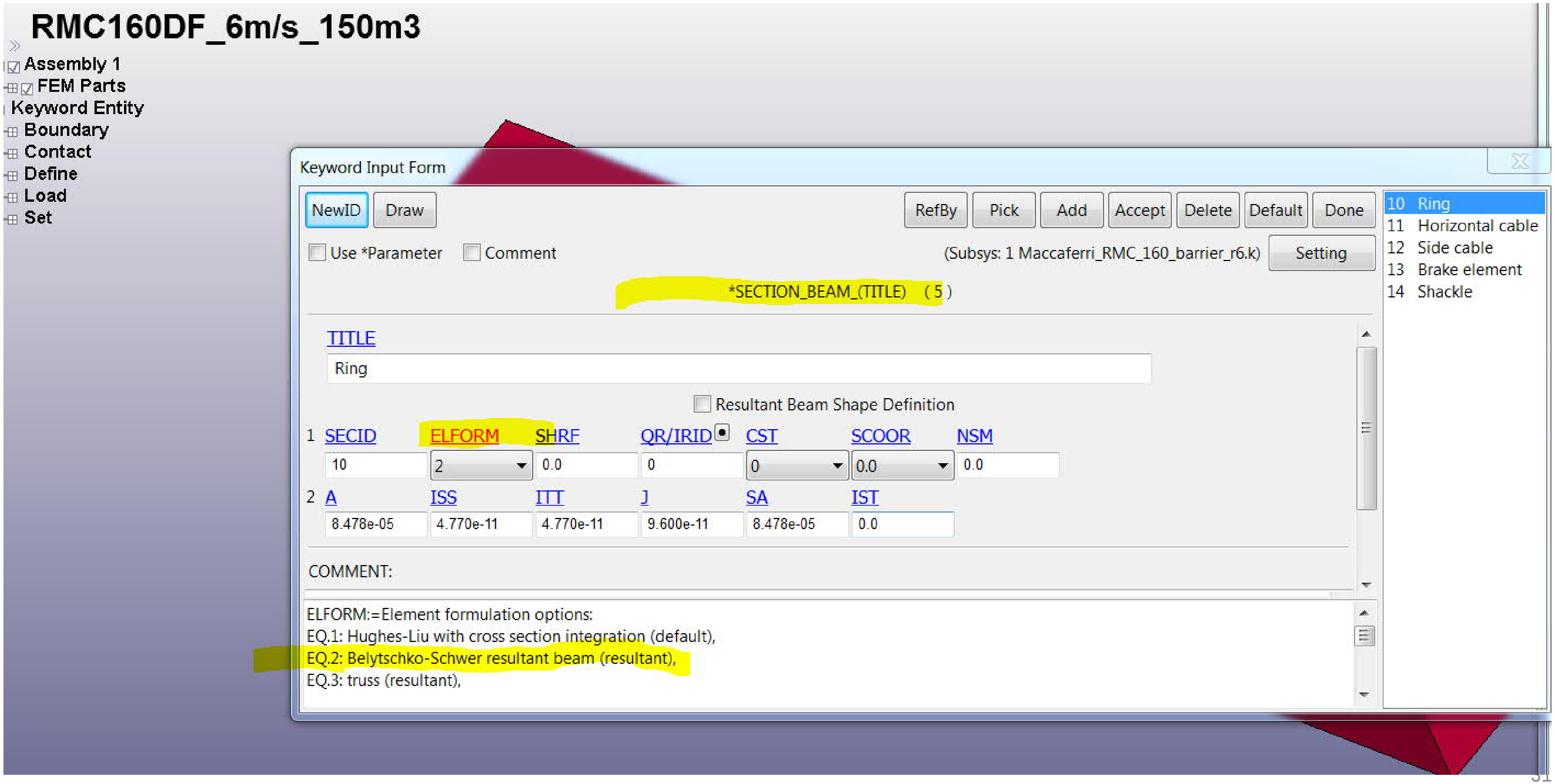
Extremely important: be reminded to define Node n_3 when generating beam element as it determines the initial orientation of the cross section!!!

Element formulation for beam elements

- Recommended type ELFORM=1 OR 2

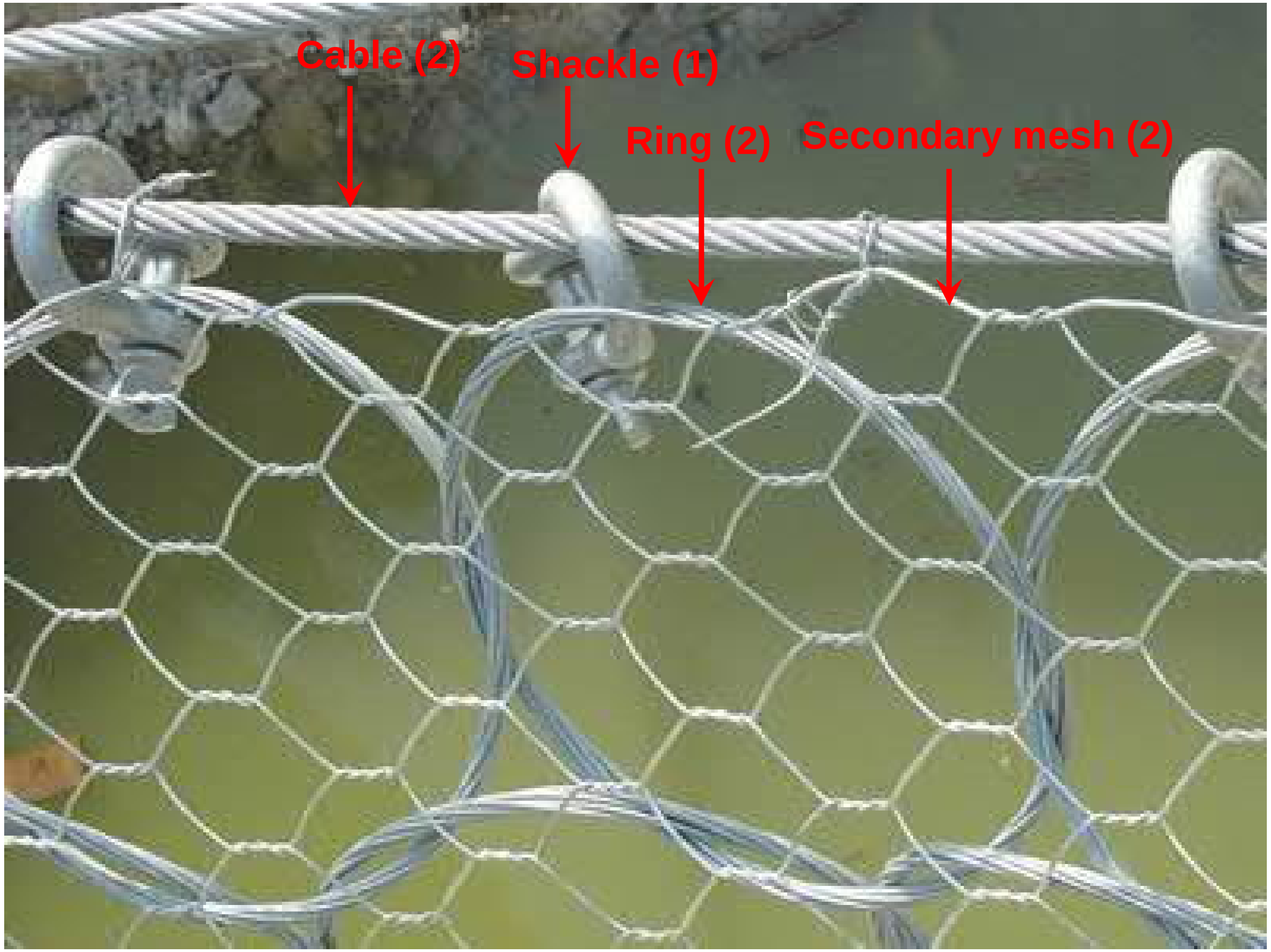


ELFORM= 2



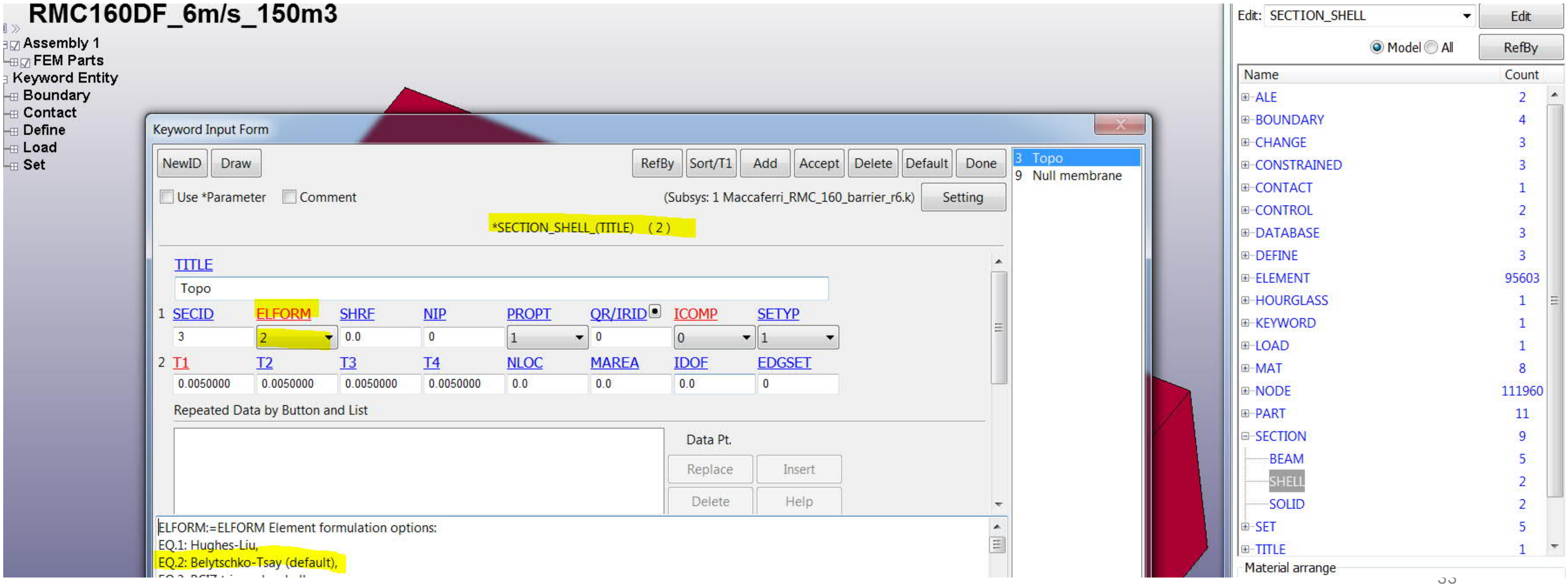
RMC160DF_6m/s_150m3
Assembly 1
FEM Parts
Keyword Entity
Boundary
Contact
Define
Load
Set
Keyword Input Form
NewID
Draw
RefBy
Pick
Add
Accept
Delete
Default
Done
Use *Parameter
Comment
(Subsys: 1 Maccaferri_RMC_160_barrier_r6.k)
Setting
*SECTION_BEAM_(TITLE) (5)
TITLE
Ring
Resultant Beam Shape Definition
1 SECID ELFORM SHRF QR/IRID CST SCOOR NSM
10 2 0.0 0 0 0.0 0.0
2 A ISS ITT J SA IST
8.478e-05 4.770e-11 4.770e-11 9.600e-11 8.478e-05 0.0
COMMENT:
ELFORM:=Element formulation options:
EQ.1: Hughes-Liu with cross section integration (default),
EQ.2: Belytschko-Schwer resultant beam (resultant),
EQ.3: truss (resultant),
10 Ring
11 Horizontal cable
12 Side cable
13 Brake element
14 Shackle

ELFORM=1 OR 2, which to choose – Example



Shell elements

- Used for modelling thin structures, e.g. topography surface, membrane etc.



Shell element formulation options

Shell Element formulation options

EQ.1: Hughes-Liu,
EQ.2: Belytschko-Tsay,
EQ.3: BCIZ triangular shell,
EQ.4: C_0 triangular shell,
EQ.5: Belytschko-Tsay membrane,
EQ.6: S/R Hughes-Liu ,
EQ.7: S/R co-rotational Hughes-Liu,
EQ.8: Belytschko-Leviathan shell ,
EQ.9: Fully integrated Belytschko-Tsay membrane,
EQ.10: Belytschko-Wong-Chiang,
EQ.11: Fast (co-rotational) Hughes-Liu,
EQ.12: Plane stress (x-y plane) ,
EQ.13: Plane strain (x-y plane)
EQ.14: Axisymmetric solid (y-axis of symmetry) - area weighted,
EQ.15: Axisymmetric solid (y-axis of symmetry) - volume weighted,
EQ.16: Fully integrated shell element (very fast),
EQ.17: Fully integrated DKT, triangular shell element ,
EQ.18: Fully integrated linear DK quadrilateral/triangular shell
EQ.20: Fully integrated linear assumed strain C0 shell
EQ.31: 1 point Eulerian Navier-Stokes
EQ.32: 8 point Eulerian Navier-Stokes

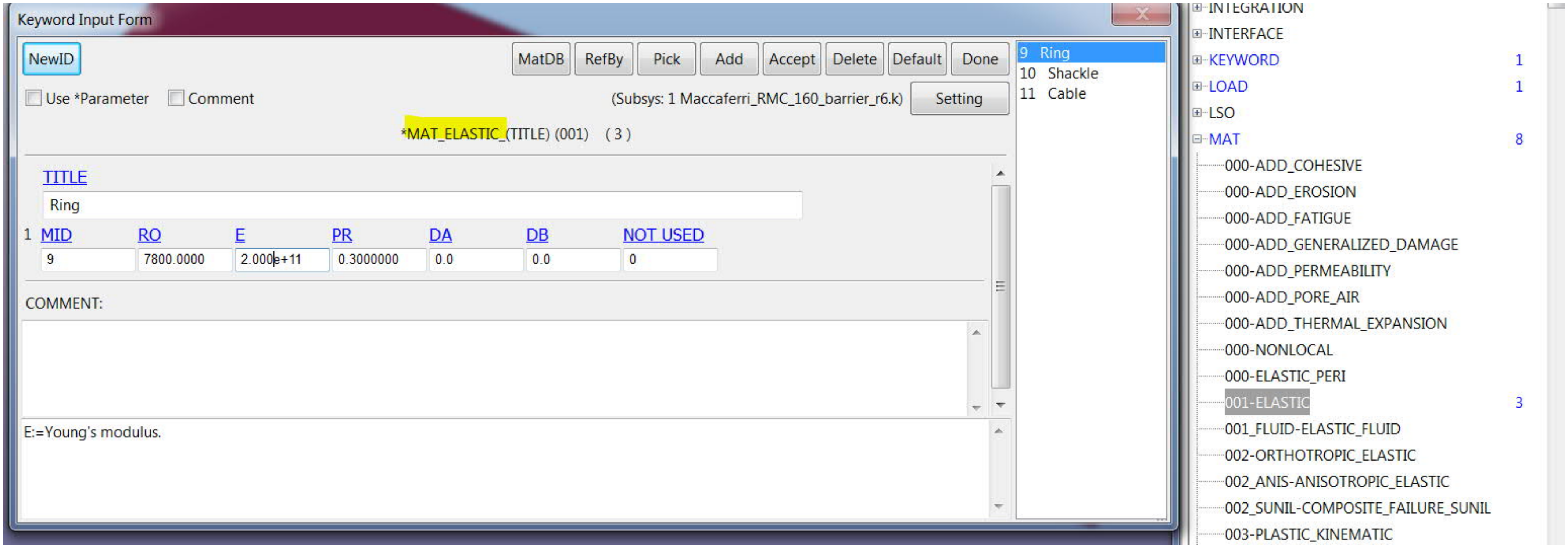
Default element formulation, good for most cases except when excessive wrapping is anticipated

Material models

Material models

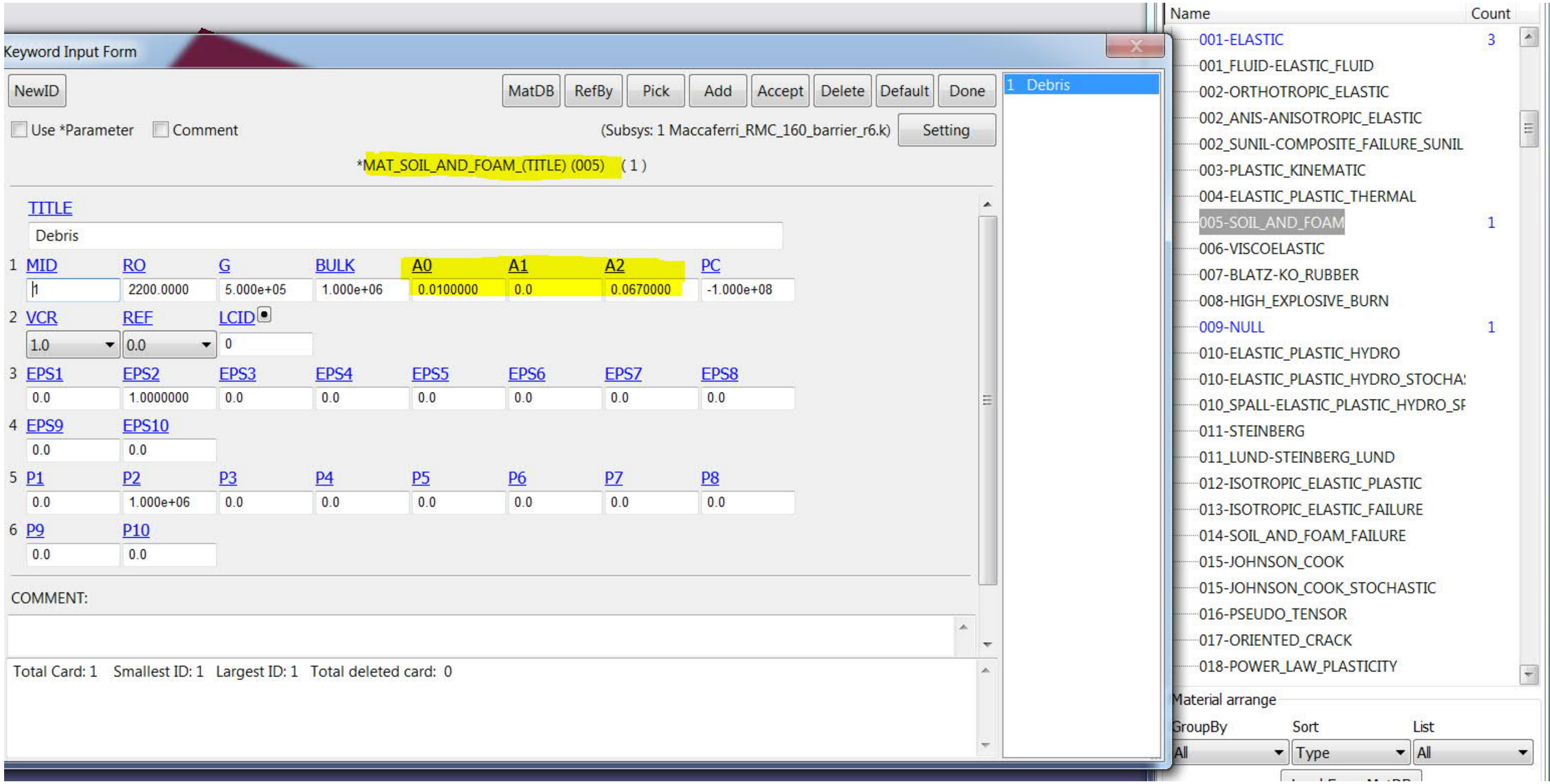
- Provide more than 200 materials models for users
- Defined under keyword *MAT
- Classification of material models
  - Elastic
  - Elastic-plastic
  - Viscoelastic
  - …
- Naming is different from what we are familiar with (Mohr-Coulomb, Modified Cam-clay, hardening soil etc.)

Example – Elastic (MAT001)



- LS-DYNA Manual: Volume II
- LS-DYNA theory manual

Material model – debris (MAT005)



- Drucker – Prager model (elastoplastic model)
- Parameter input: NO conventional concept of cohesion, frictional angle

Key input parameters of Drucker – Prager model

$$A_2 = \left(\frac{-sin\phi'}{cos\theta - \left(\frac{1}{\sqrt{3}}\right)sin\theta sin\phi'}\right)^2$$

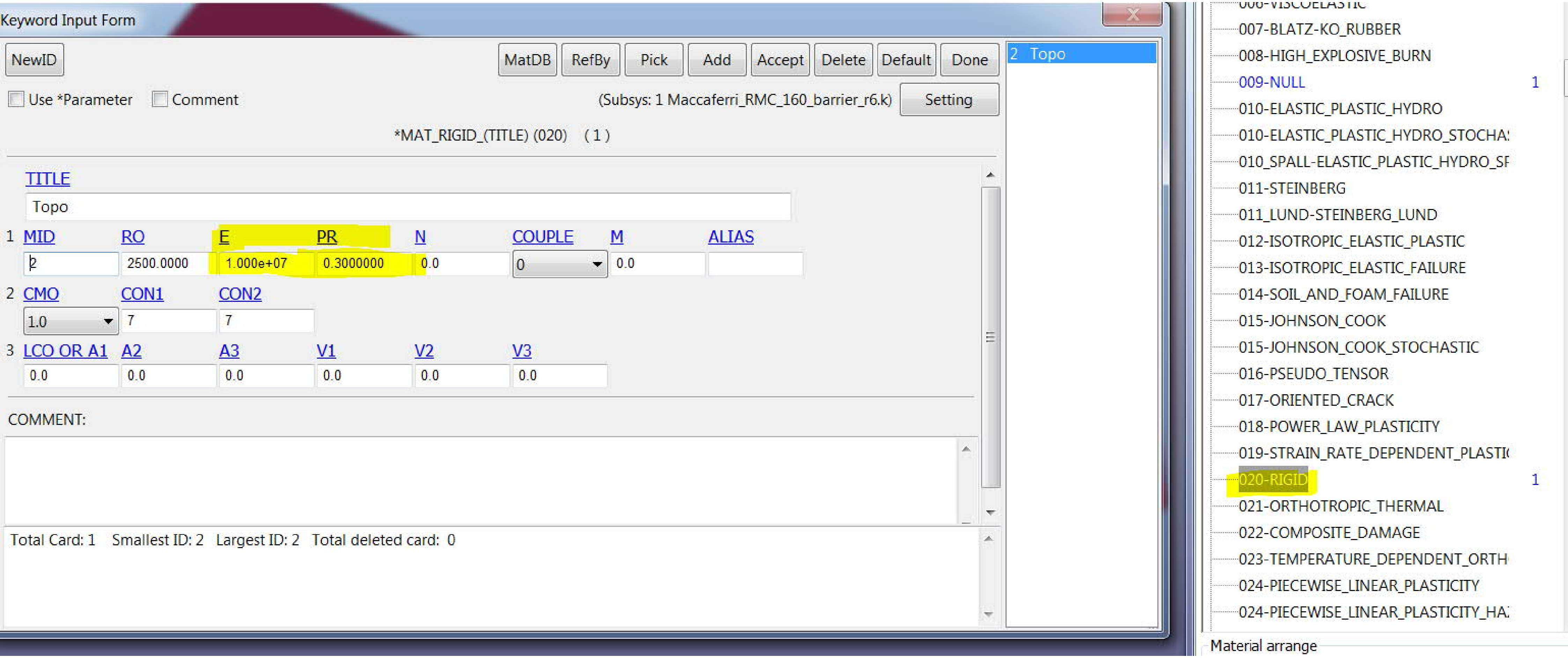
$$A_1 = \frac{-sin\phi'}{cos\theta - \left(\frac{1}{\sqrt{3}}\right)sin\theta sin\phi'} \times \frac{-ccos\phi'}{cos\theta - \left(\frac{1}{\sqrt{3}}\right)sin\theta sin\phi'}$$

c: cohesion
ϕ': internal friction angle
θ: Lode Angle, usually assume = 0

$$A_0 = \left(\frac{-ccos\phi'}{cos\theta - \left(\frac{1}{\sqrt{3}}\right)sin\theta sin\phi'}\right)^2$$

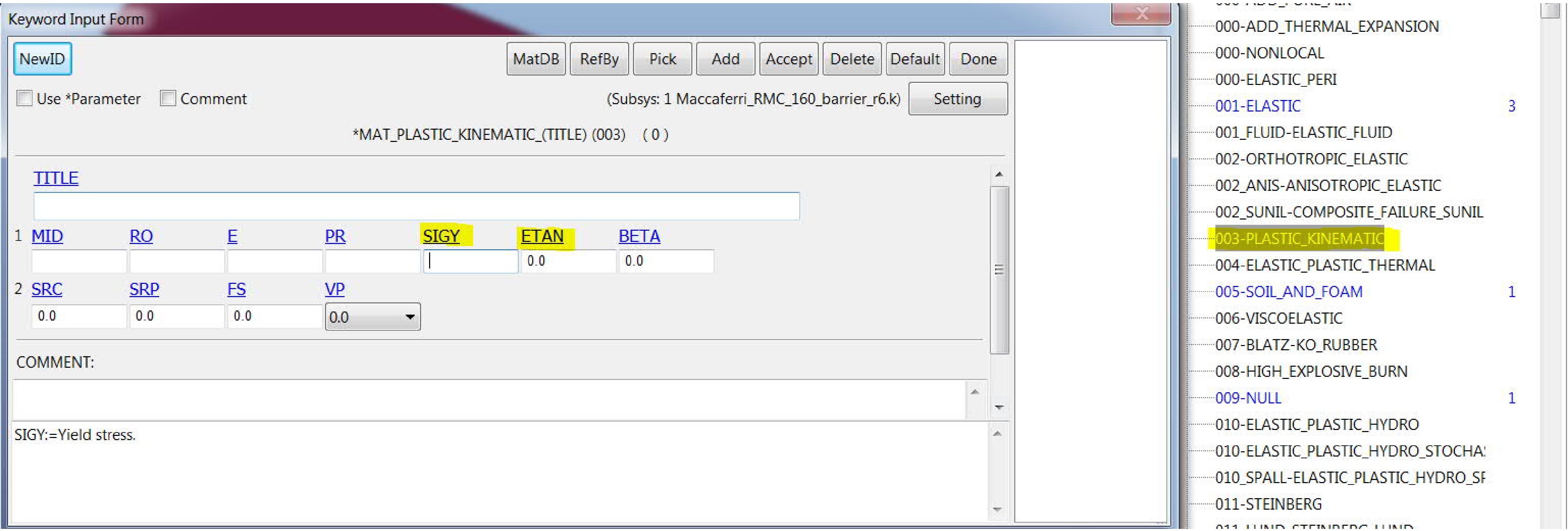
Material model – MAT_RIGID(MAT020)

- Topography
- Boulders



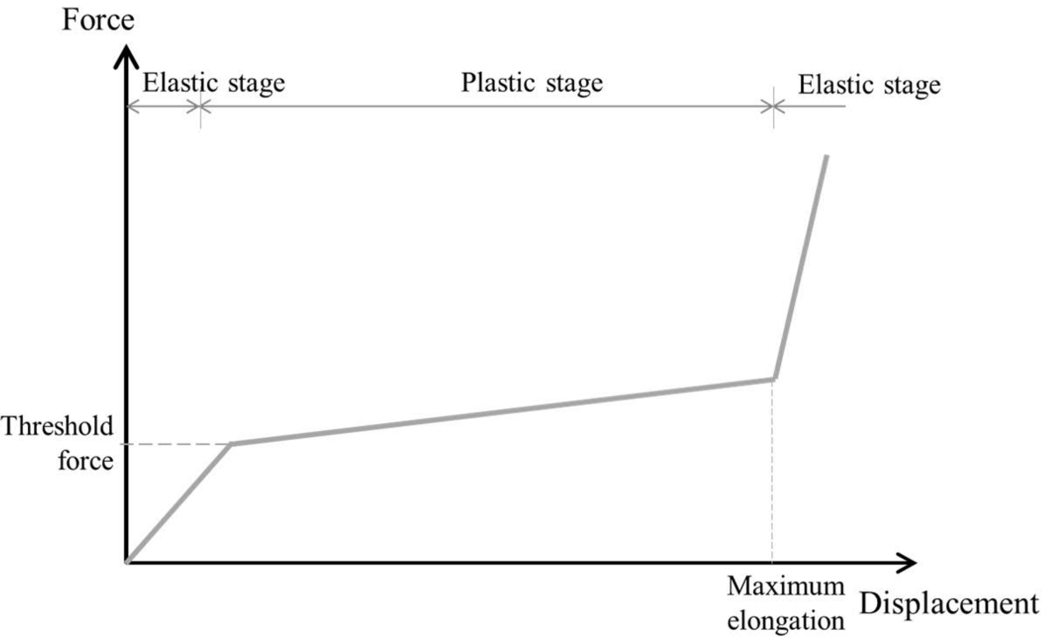
Material model – cables, post, rings and shackles etc.

- A couple of choices exist
  - Elastic only (MAT001)
  - Elastic-plastic (MAT003)

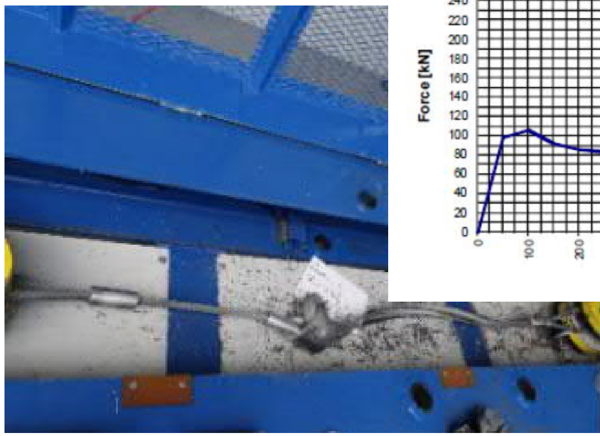


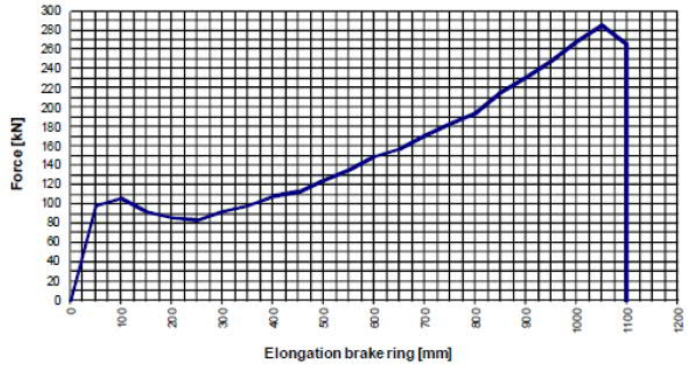
Material model – brake elements

Working principles



Before test





After test

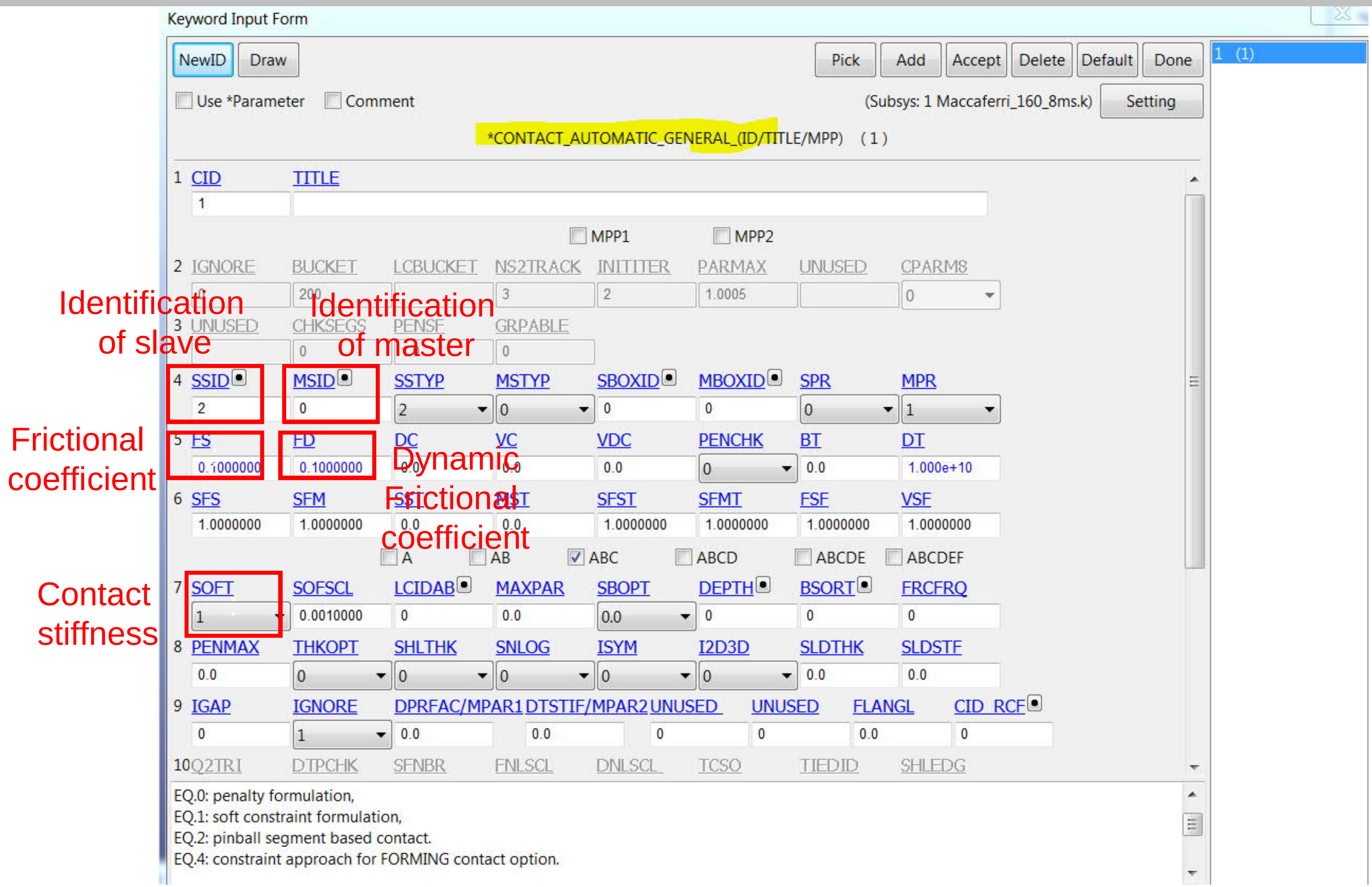
- Possible choices: e.g. MAT094 (Inelastic_Spring_Discrete_Beam), MAT003
- Other options are encouraged as long as justification is made

Contact modelling

Types of contact

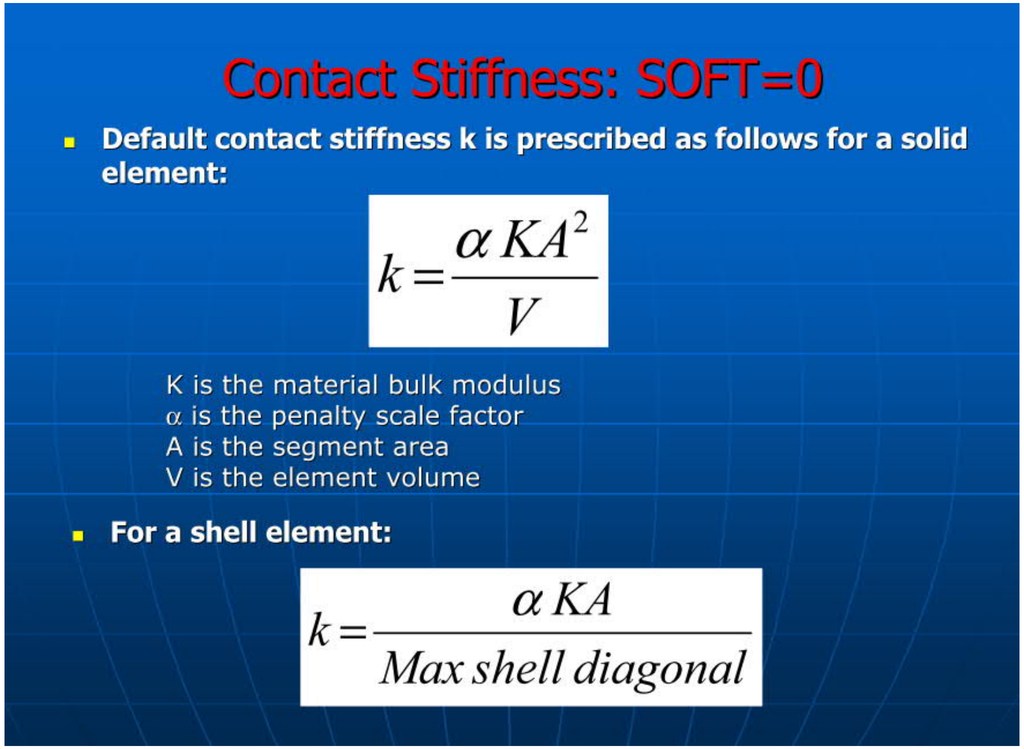
- Purpose of contact: allow different parts interact with each other and thus load transfer occurs
- Typically used:
  - *Surface to surface*, e.g. boulder & topography
  - *Node to surface*, e.g. boulder & flexible barrier
  - *Single surface*, e.g. components of flexible barrier
  - …

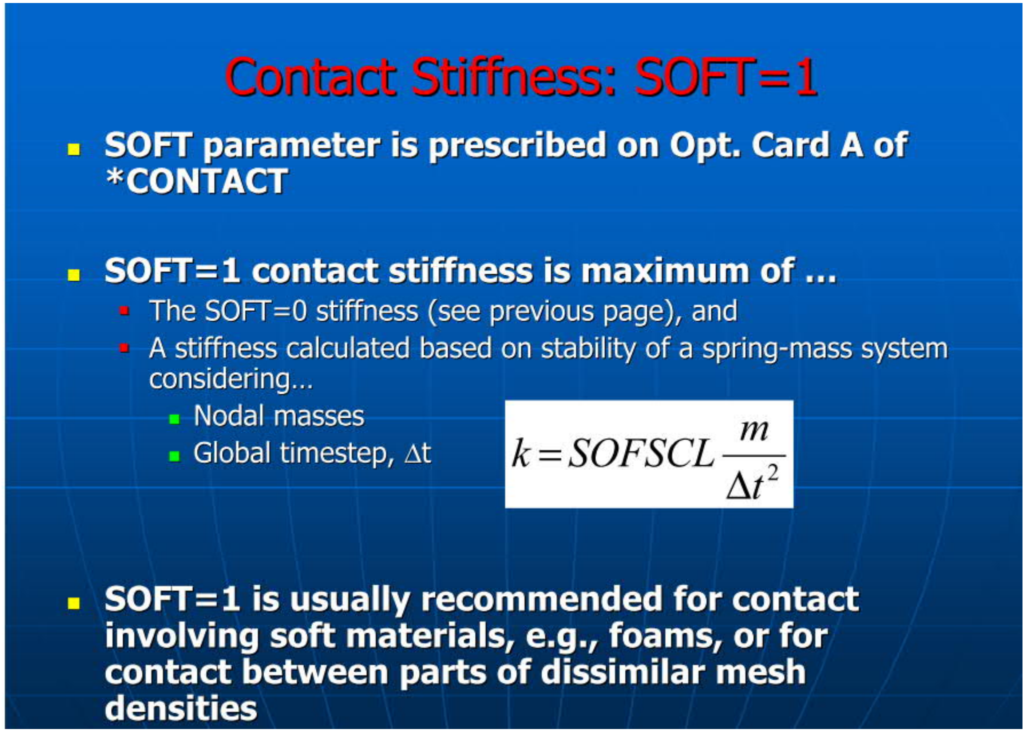
Contact input card



Contact force calculating method

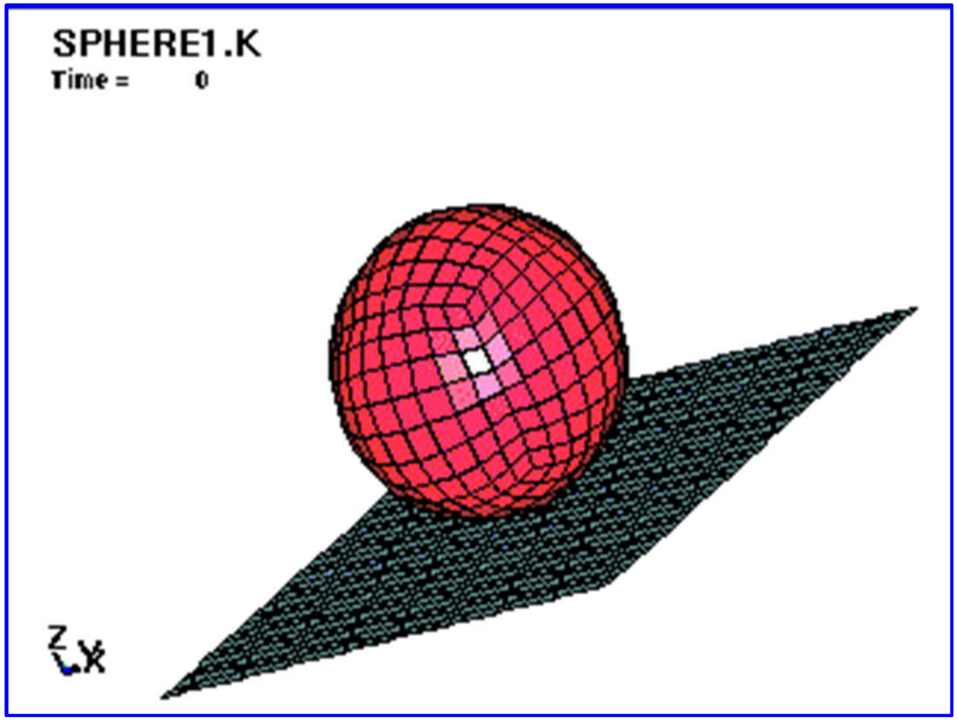
- Most commonly used: penalty-based
  - Normal direction resist penetration: **contact stiffness**
  - Tangent direction resist friction: frictional coefficient





Surface to surface contact

- Utilize two-way treatment: master\slave distinction not important

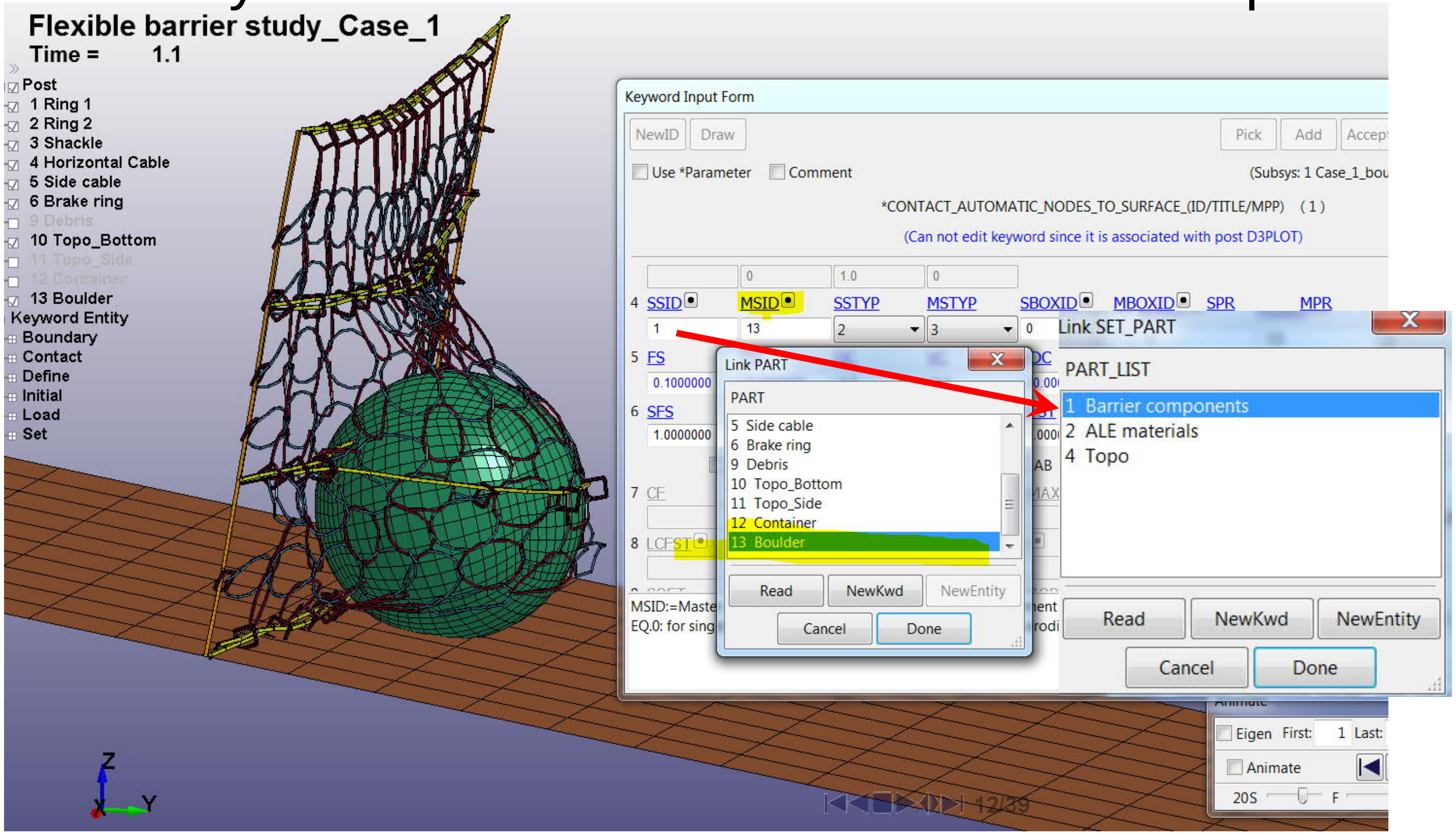


Automatic surface to surface

- Efficient and robust penetration searching method

Nodes to surface contact

- Utilize one-way treatment: master\slave distinction important



Automatic nodes to surface

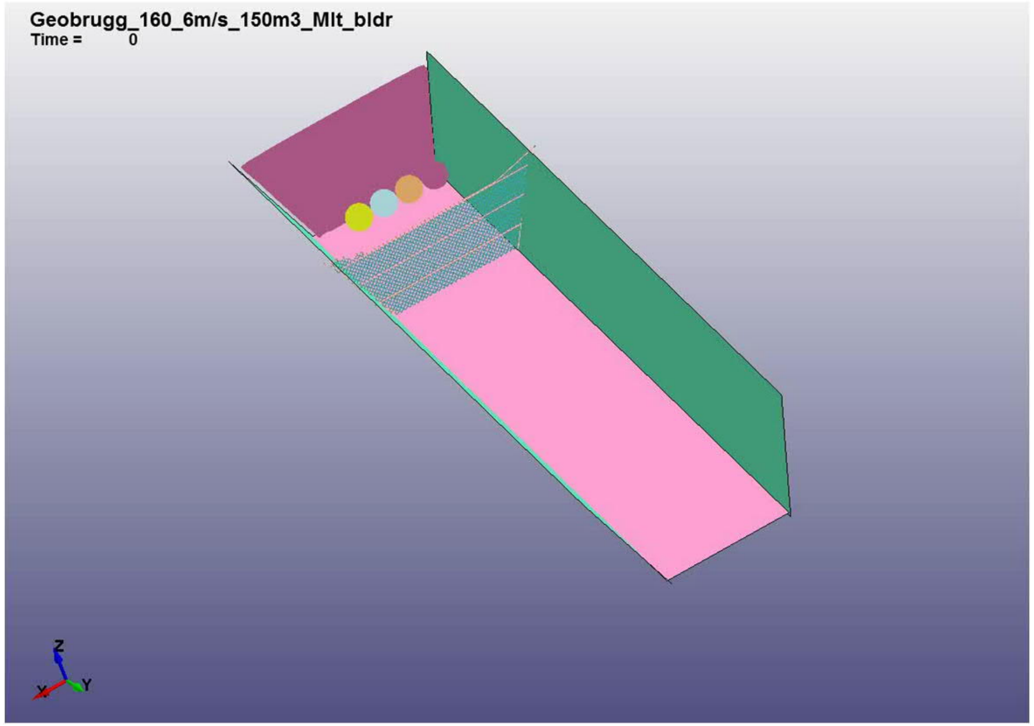
- Efficient and robust penetration searching method

Single surface contact

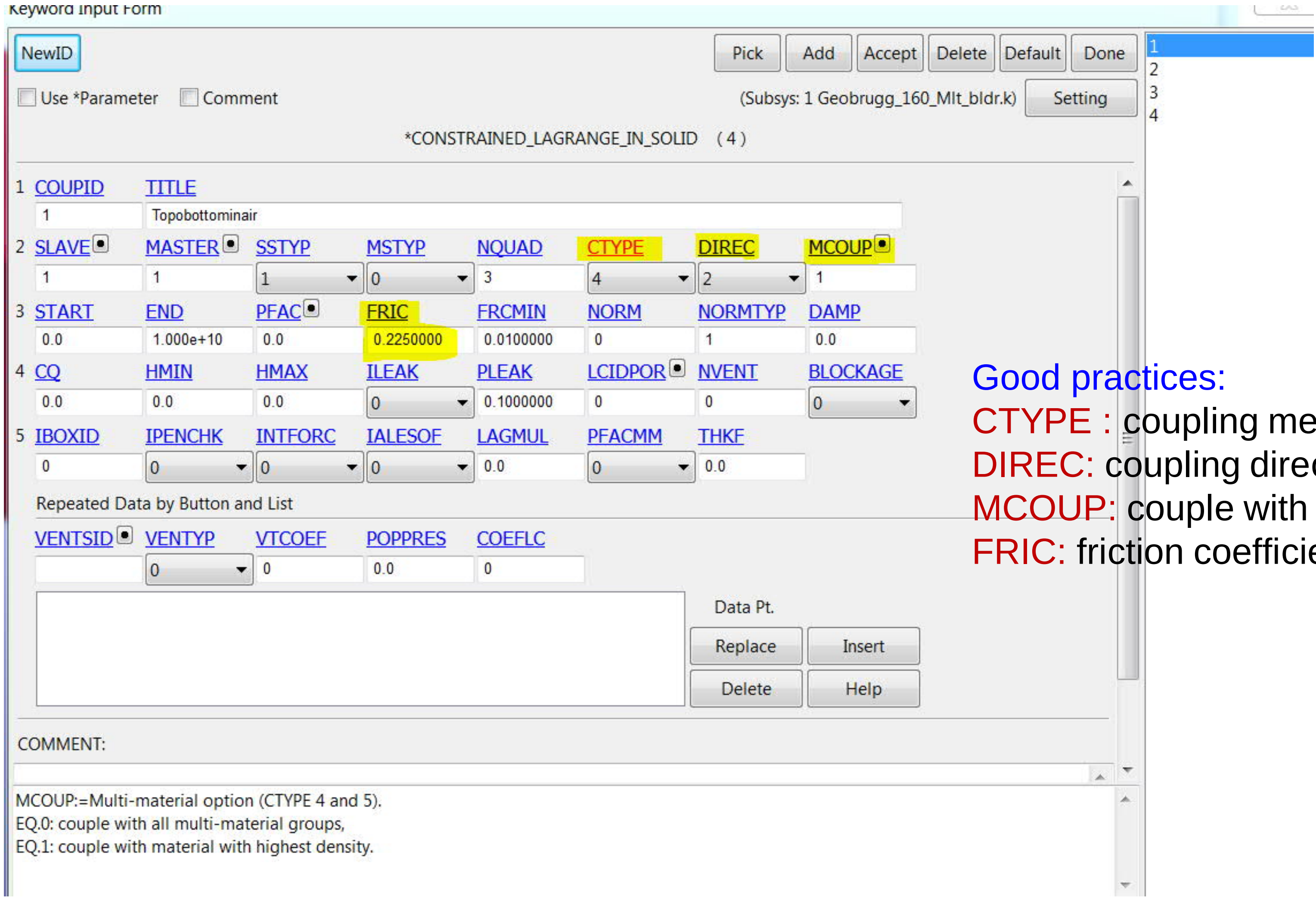
- Concept of single surface contact
  - Assumes that everything contacts everything else
  - *Automatic_general*
    - Computationally expensive but very robust
    - *Single-surface* formulation and only the slave side is defined
    - Good for edge-to-edge, beam-to-beam contact (e.g. flexible barrier components)
  - *Automatic_single_surface*
    - less CPU expensive form of *Automatic_general*
    - Most common contact used in impact simulation

ALE contact with *Lagrangian*

- *Constraint_Lagrange_In_Solid*
  - Generate forces that resist penetration of the ALE through the Lagrangian parts



Constraint_Lagrange_In_Solid



Good practices:

CTYPE : coupling method, Chose 4 (penalty coupling)

DIREC: coupling direction, Chose 2 (normal direction)

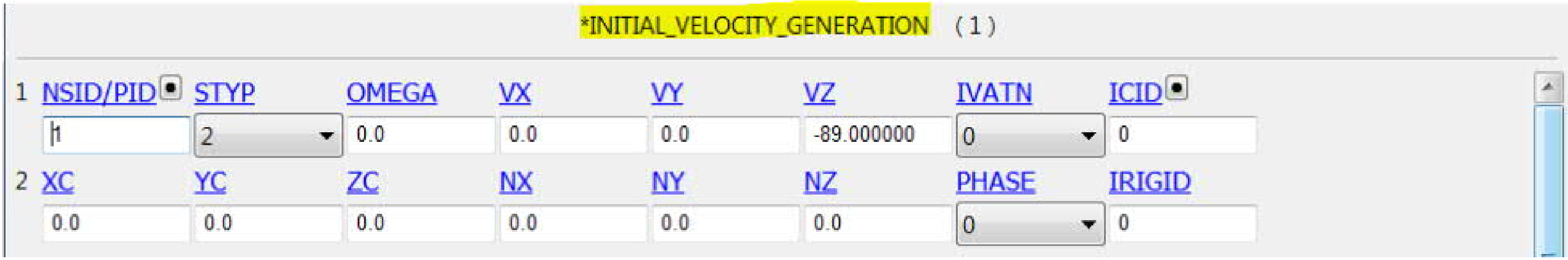
MCOUP: couple with which multi-material group

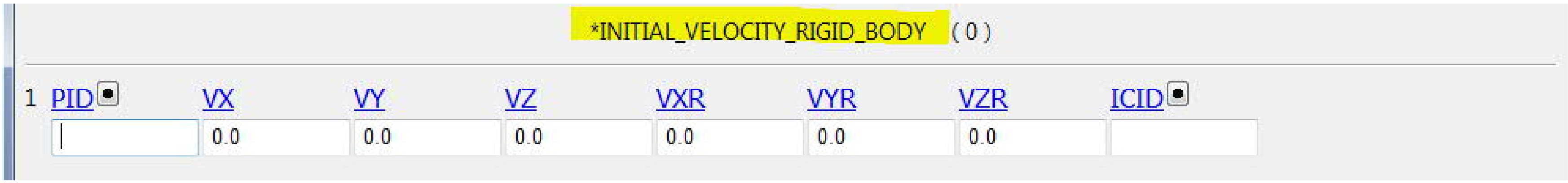
FRIC: friction coefficient, calculated from friction angle

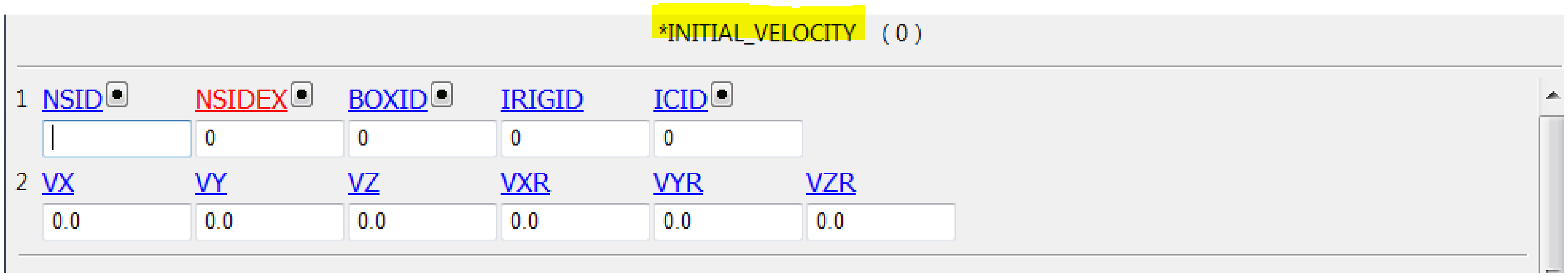
Initial and boundary conditions

Initial conditions

Keyword	Operation object	Rotational velocity	Translational velocity	Remark
Initial_Velocity_Generation	Part or node set			Must not be used with *Initial_velocity
Initial_Velocity_Rigid_Body	Rigid Part	√	√	e.g. boulder
Initial_Velocity	Node set			e.g. define nodes of boulder as a set

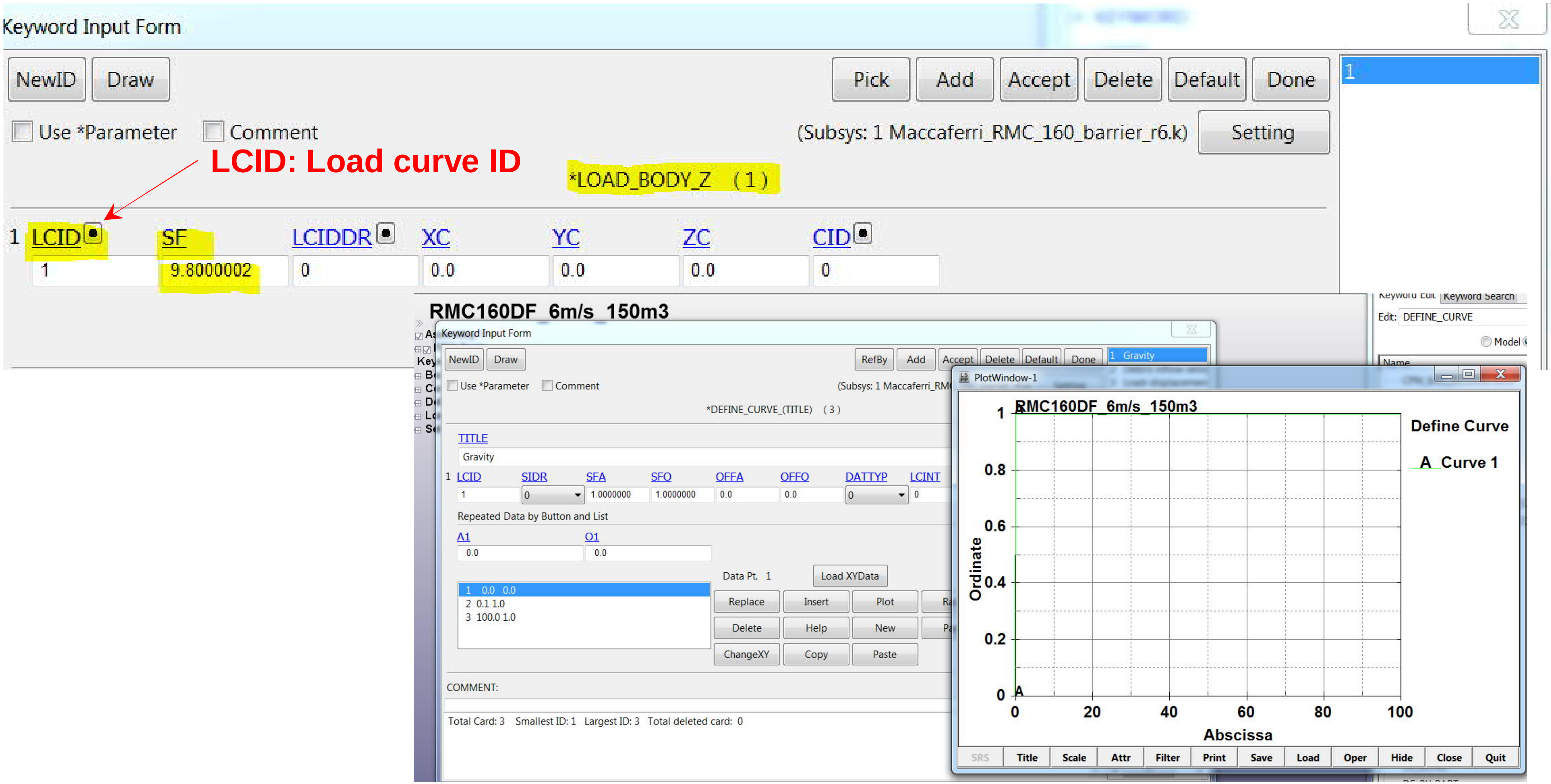






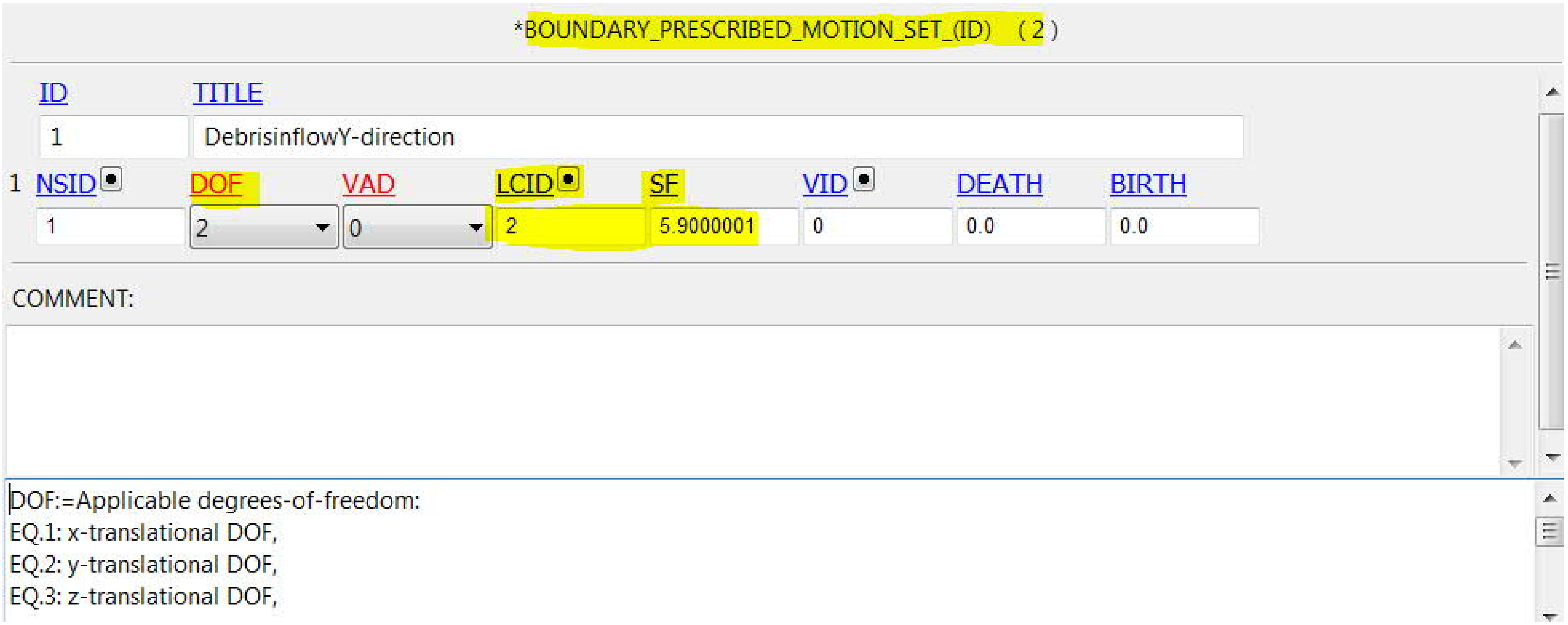
Gravity

- *Load_Body_Z



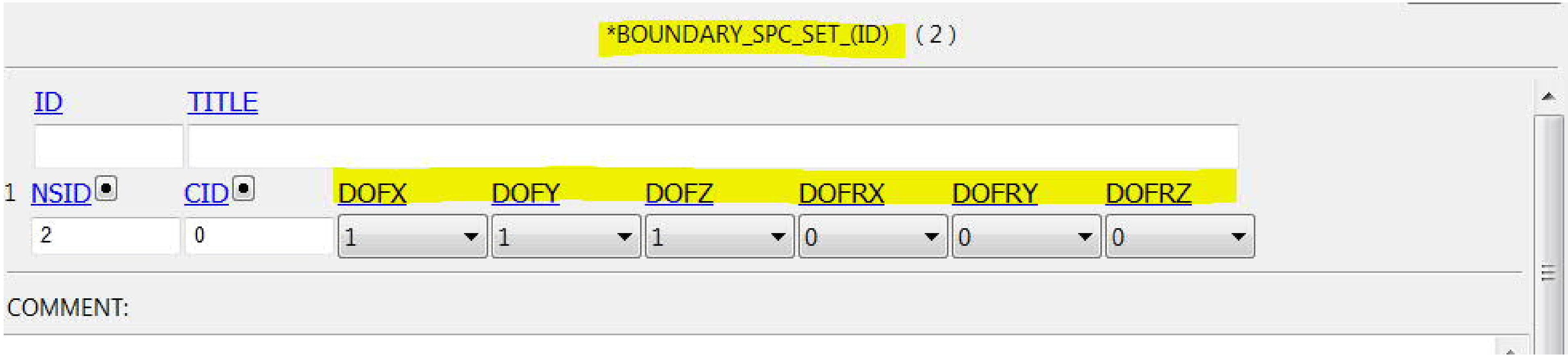
Boundary conditions

- Movement
  - e.g. *Boundary_Prescribed_Motion_Set



Displacement boundary conditions

- Constraints
  - e.g. *Boundary_SPC_Set



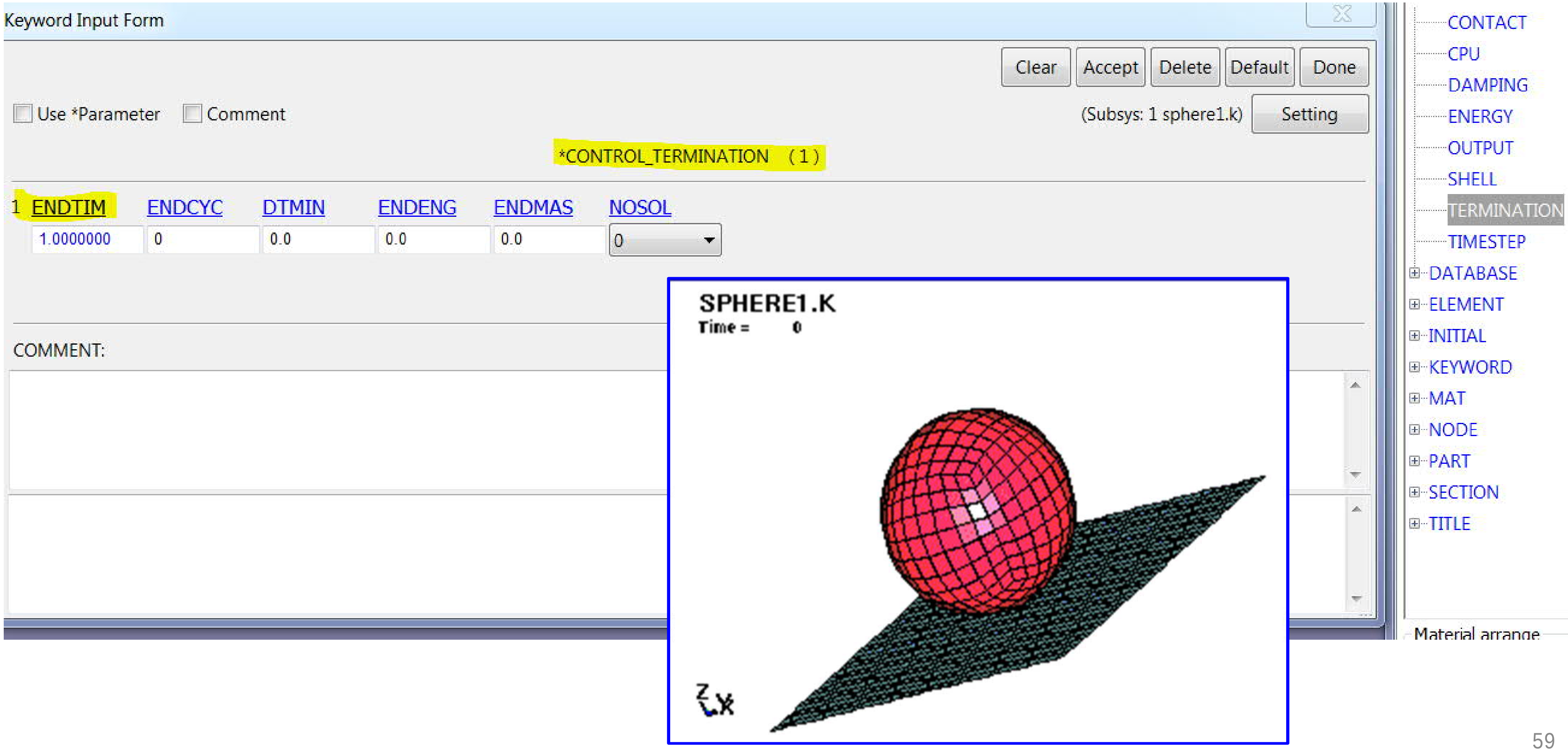
Control parameters

Commonly used

- *Control_Termination
- *Control_Timestep
- *Control_Energy

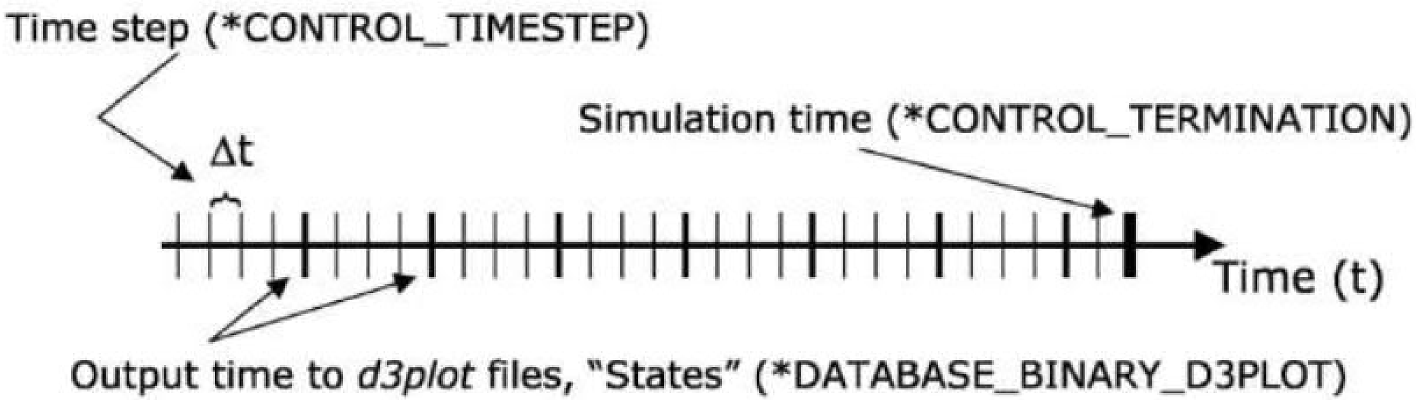
Termination

- The time when to stop computation



Timestep

- The time step to proceed explicit calculation
- Time step size depends on
  - Element size, element formulation
  - Material properties, e.g. modulus

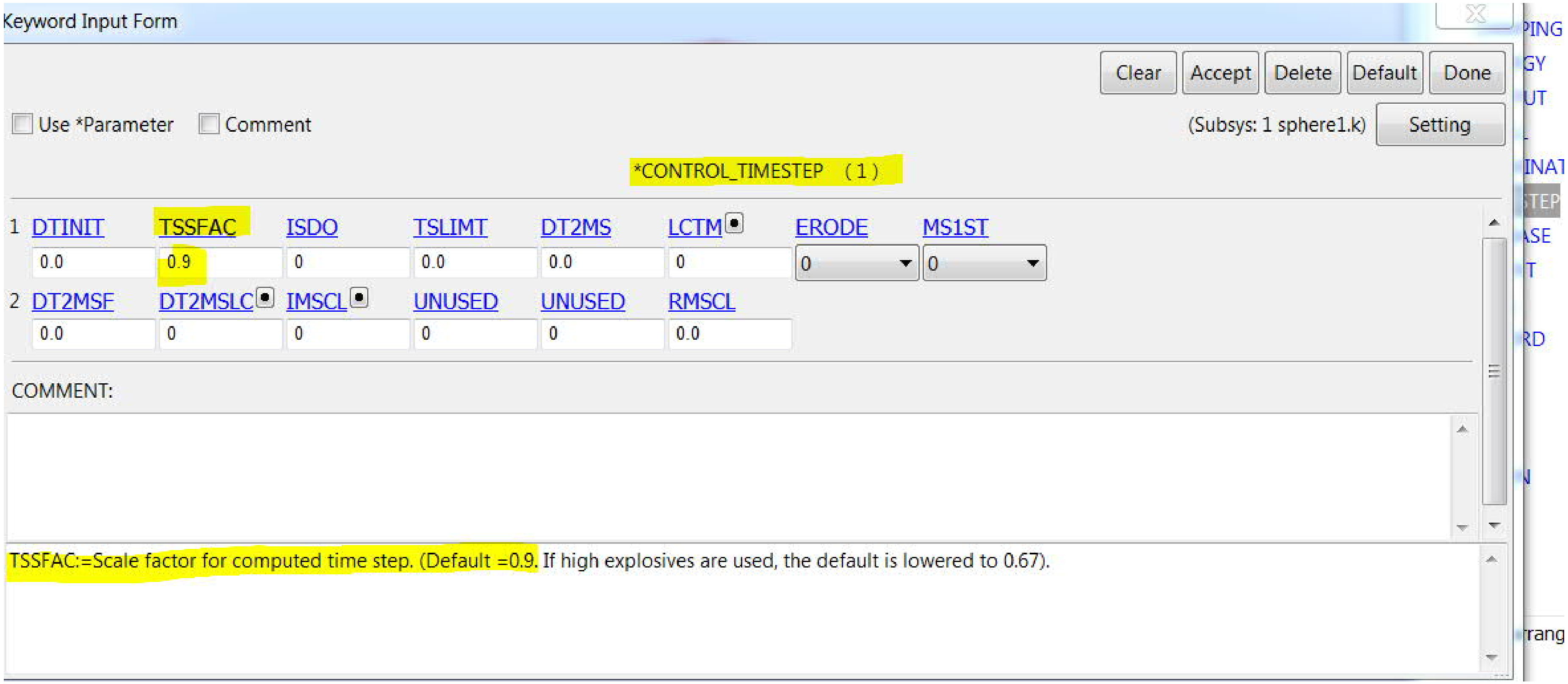


$$C_{AccousticWaveSpeed} = \sqrt{\frac{E_{Material}}{\rho_{Material}}}$$

$$\Delta ExplicitTimestep = \frac{Length_{Element}}{C_{Wavespeed}}$$

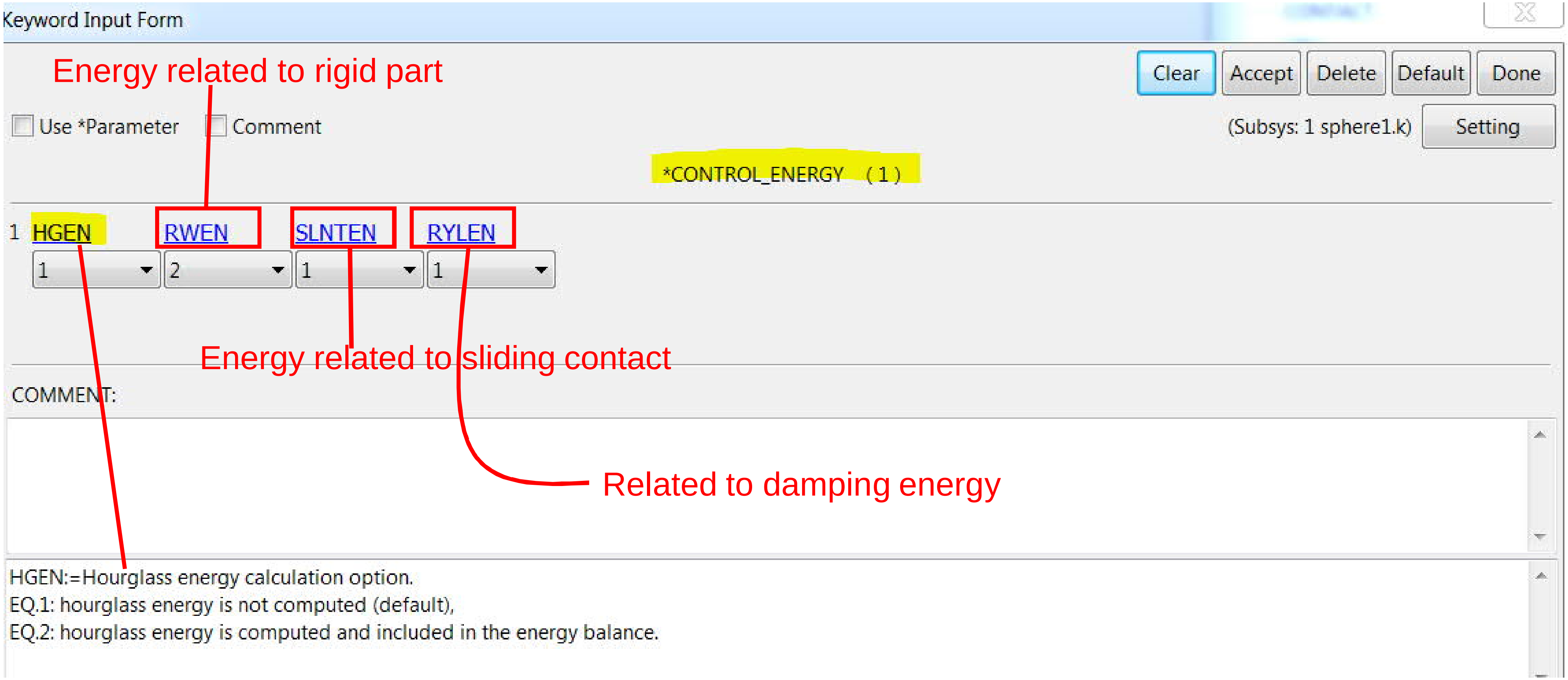
$$\Delta Timstep_{CFL} = (0.9)\Delta ExplicitTimestep$$

Scale factor for computed time step



Tips: if ALE involved, have the time step scale factor reduced from the default of 0.9 to **somewhere around 0.6** in order to maintain a stable solution

Energy



Keyword Input Form
Energy related to rigid part
Clear
Accept
Delete
Default
Done
Use *Parameter
Comment
(Subsys: 1 sphere1.k)
Setting
*CONTROL_ENERGY (1)
1 HGEN
RWEN
SLNTEN
RYLEN
1
2
1
1
Energy related to sliding contact
COMMENT:
Related to damping energy
HGEN:=Hourglass energy calculation option.
EQ.1: hourglass energy is not computed (default),
EQ.2: hourglass energy is computed and included in the energy balance.

Remark on Energy in LS-DYNA

$$\underbrace{E_{kin} + E_{int} + E_{si} + E_{rw} + E_{damp} + E_{hg}}_{\text{total energy } E_{total}} = E^0_{kin} + E^0_{int} + W_{ext}$$

$$\begin{aligned}
E_{kin} &= \text{current kinetic energy} \\
E_{int} &= \text{current internal energy} \\
E_{si} &= \text{current sliding interface energy (including friction)} \\
E_{rw} &= \text{current rigid wall energy} \\
E_{damp} &= \text{current damping energy} \\
E_{hg} &= \text{current hourglass energy} \\
E^0_{kin} &= \text{initial kinetic energy} \\
E^0_{int} &= \text{initial internal energy} \\
W_{ext} &= \text{external work}
\end{aligned}$$

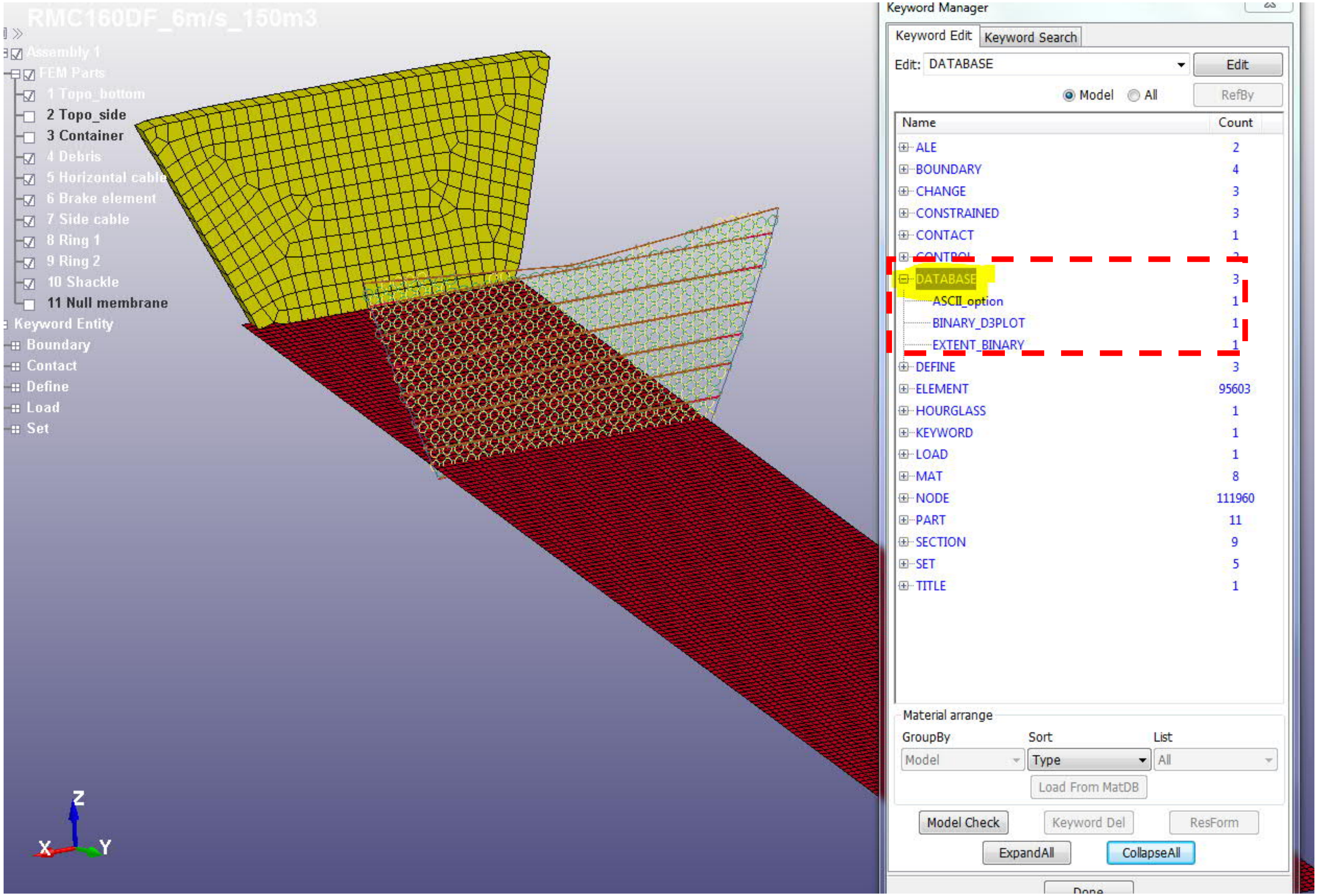
Potential energy is NOT included in this energy balance equation!!

Unit system – keep consistent

Mass	Length	Time	Force	Stress	Energy
kg	m	s	N	Pa	N·m (J)
g	mm	ms	N	MPa	N·mm
kg	mm	s	mN	kPa	mN·mm
…	…	…	…	…	…

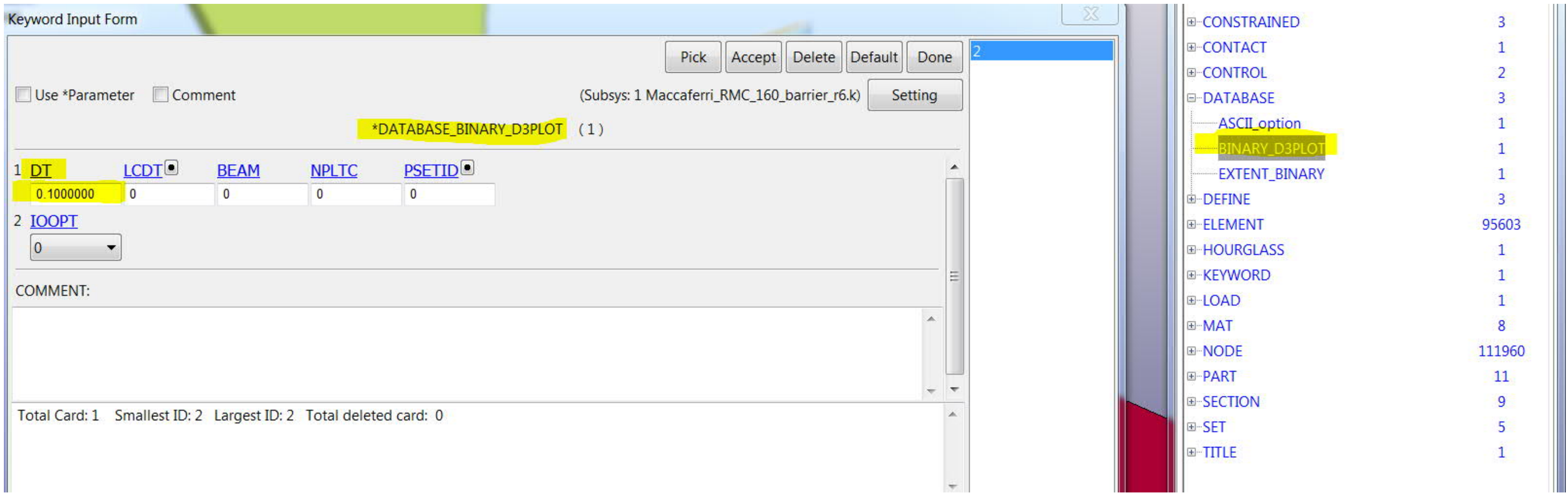
Post-processing guidelines

Before running a model



Keywords defining what data to output

Keyword	Output option	Remark
*Database_Binary_D3plot	Set DT	DT, time interval to output d3plot file used for animation, e.g. DT=0.1
*Database_ASCII_Option	GLSTAT, MATSUM,RCFORC SLEOUT, SPCFORC, NCFORC	Minimum recommended set, in ASCII format
*Database_Extent_Binary	IEVER=1, STSSZ=3	Output individual d3plot file at every time interval to avoid result file too large
*Database_Binary_Intfor	Set DT	Contact forces and stresses that can be used for fringe plotting



Output files useful in post-processing ALE simulation

Keyword	Output option	Remark
*Database_FSI		A file named as dbfsi in ASCII format, reports time history of coupling forces as well as coupling pressure
*Database_Binary_FSIFOR#	Set DT	A binary database can be read into LS-PrePost to enable fringe plots of coupling pressure and forces

Certain procedures should be followed when using this keyword, refer to User Manual (Vol I)

Concluding remarks

Modelling check list - 1

➢Mesh considerations

- Does the mesh size give a reasonable time step?
- Are reasonable aspect ratios for solids and shells being used
- If using under-integrated elements, is hourglass energy small enough or the level of hourglassing acceptable?
- Are duplicate elements / nodes avoided?

➢Hourglass

- Are ALE fluids, which require lowering the hourglass coefficients, being used?

➢Material models

- Are strain-rate effects important?
- Has a reasonable range for the material input curves been defined, so that rediscretization won't affect the resolution in the area of interest?

Modelling check list - 2

- Contacts
  - Have checks for redundant contacts been completed?
  - Have checks for significant penetration between contacting parts been completed?
- General quality check
  - Is the time-step small enough given the relative velocity of the impact, and, if not, has reducing the time step scaling factor been considered?
  - Is the time-step unreasonably unstable and small that a revisit to time step control parameters needed
- Output data
  - Are anticipated results (node force, axial force etc.) that would be useful for interpretation all defined in the *Database keyword and relevant cards?
- Finally, for all categories
  - **As a beginner, if not sure, use default setting**

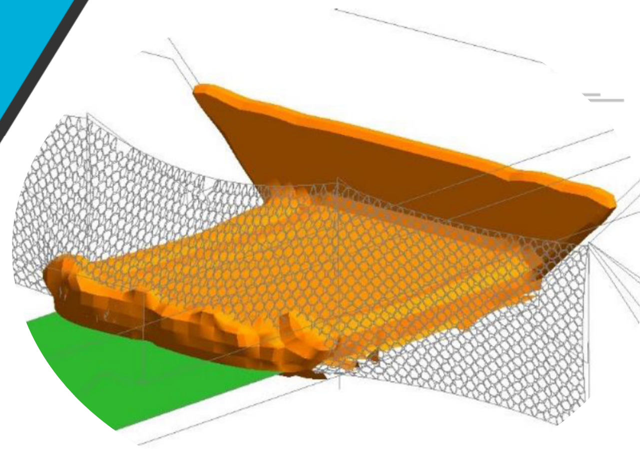
Useful references

- https://www.dynasupport.com/manuals
  - LS-DYNA User Manual (Vol I to III, latest version)
  - LS-DYNA Theory Manual (2017 Draft version)
- https://www.dynasupport.com/tutorial
- LS-DYNA Aerospace Working Group
  https://awg.lstc.com/tiki-index.php?page=Resources

Thank you.

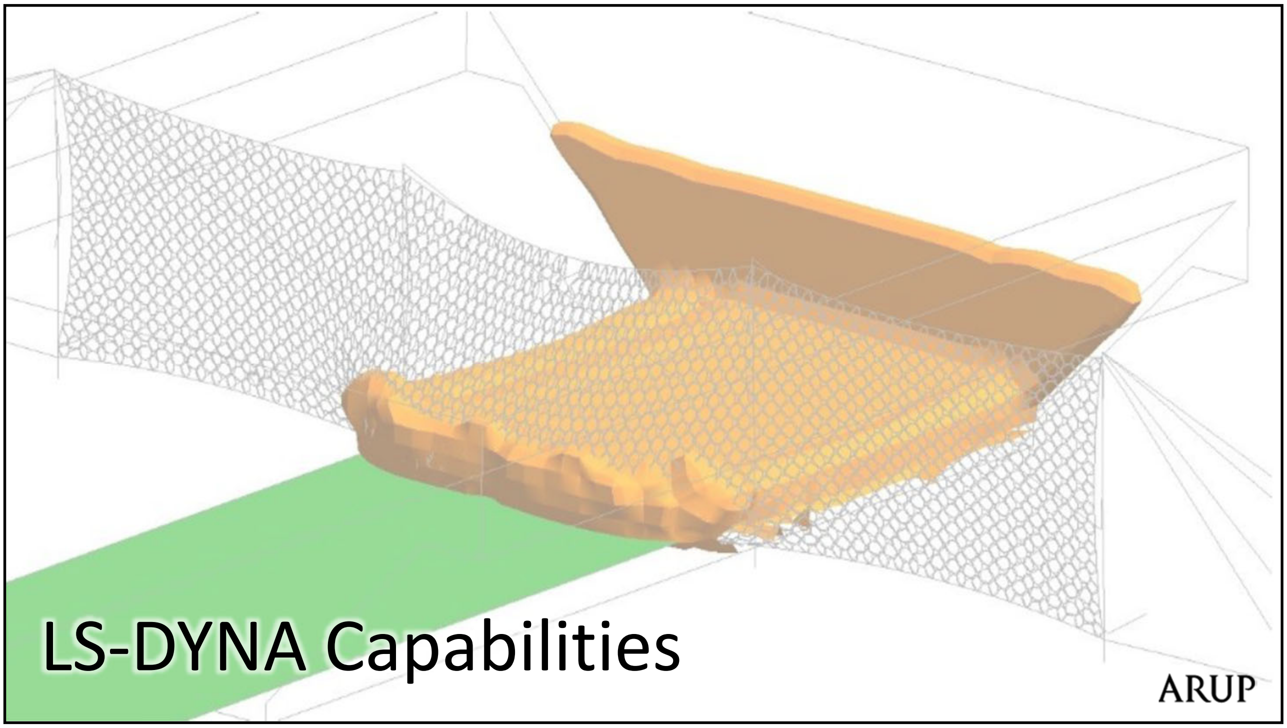
Design Experience Sharing and Demonstration of Using LS-DYNA

Jack Yiu and Arthur Cheung
Ove Arup & Partners Hong Kong Limited
16 April 2019



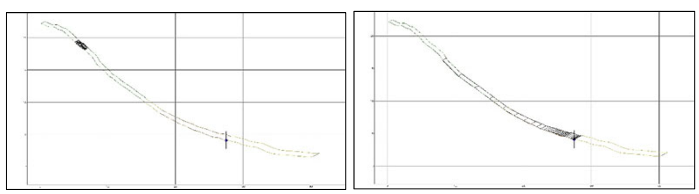
Outline

- LS-DYNA Capabilities
- Debris Mobility Modelling
  - Model Setup Illustration
  - Design Case Sharing – Fo Tan
- Structural Analysis of Flexible Barrier
- Couple Analysis with Barrier
  - Design Case Sharing – Flexible Barrier Performance Optimisation



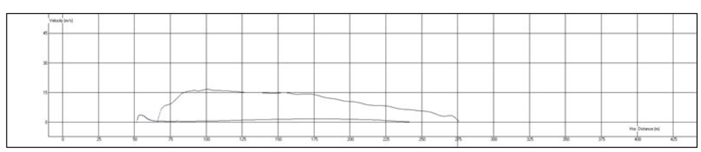
Current Approach of Flexible Barrier Design

- Debris mobility prediction using simplified 2D analysis e.g. DAN/W
- Debris runout path is pre-defined and much idealised



Debris run-out prediction using DAN/W (from source to downslope)

- Debris volume and maximum frontal velocity at a particular check point for flexible barrier design



Velocity of the debris respect to horizontal run-out distance

- Two approaches for the barrier design:
    - Energy approach: select a rockfall barrier with energy rating that match the predicted maximum kinetic energy
    - Force approach: pseudo-static force to explicitly design the barrier

Explore the Possibility of Using Advanced Numerical Tools

- Shortcoming of the existing approaches:
  - Energy approach: energy rating of barrier was based on rock fall tests, not debris flow
  - Force approach: interaction of debris and barrier not considered, hence the flexible barrier design will be too conservative and onerous.

- Arup works with the GEO to investigate the use of advanced numerical methods to study the interaction of debris flow and flexible barrier → LS-DYNA, a multi-purpose finite element program for linear and non-linear mechanics, large deformation

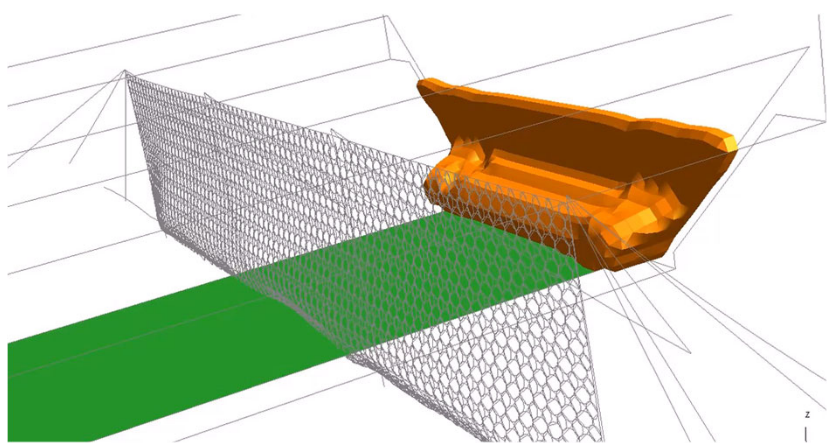
- The objective of the previous works:
  - Provide better prediction of debris mobility for flexible barrier design
  - Improve the accuracy and cost-effectiveness of flexible barrier design
  - Provide insight for the development of standardised and rationalised design method

ARUP

Advanced numerical package used – LS-DYNA

LS-DYNA

- LS-DYNA is a multi-purpose finite element program for linear and non-linear mechanics



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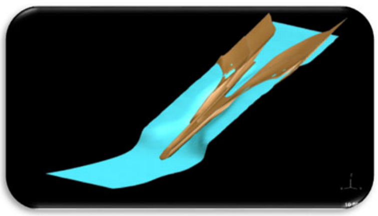
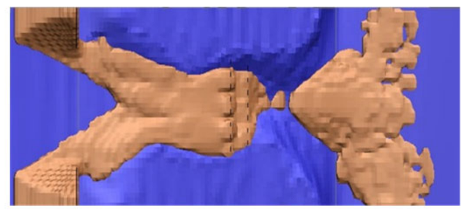
Why LS-DYNA?

- Track records on impact analyses
- Able to model large deformation and movement of debris mass with the use of advanced finite element meshing method
- Able to simulate coupled soil-structure interaction
- Flexible to make changes to codes for different applications



Conventional meshing method in Finite Element analysis fails to capture large soil deformation



LS-DYNA ALE meshing technique allows the simulation of soil structure interaction between baffles and landslide debris

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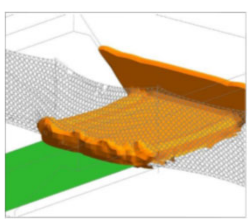
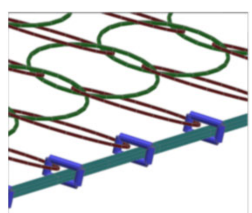
Development since 2012

2012 - 2014



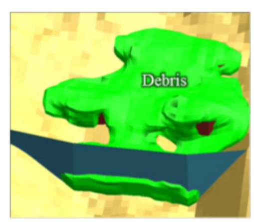
The **Interactions** between Landslide Debris and Flexible Barriers

2014 - 2016



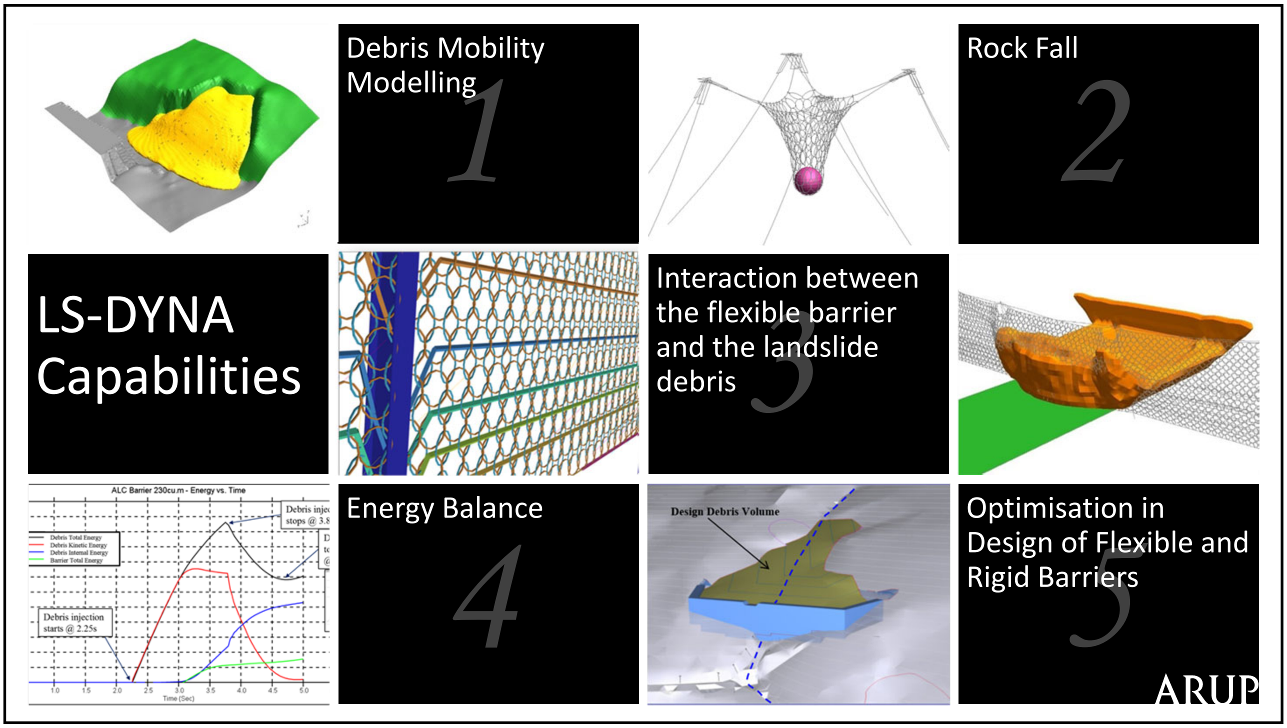
Energy Balance of Flexible Barrier System

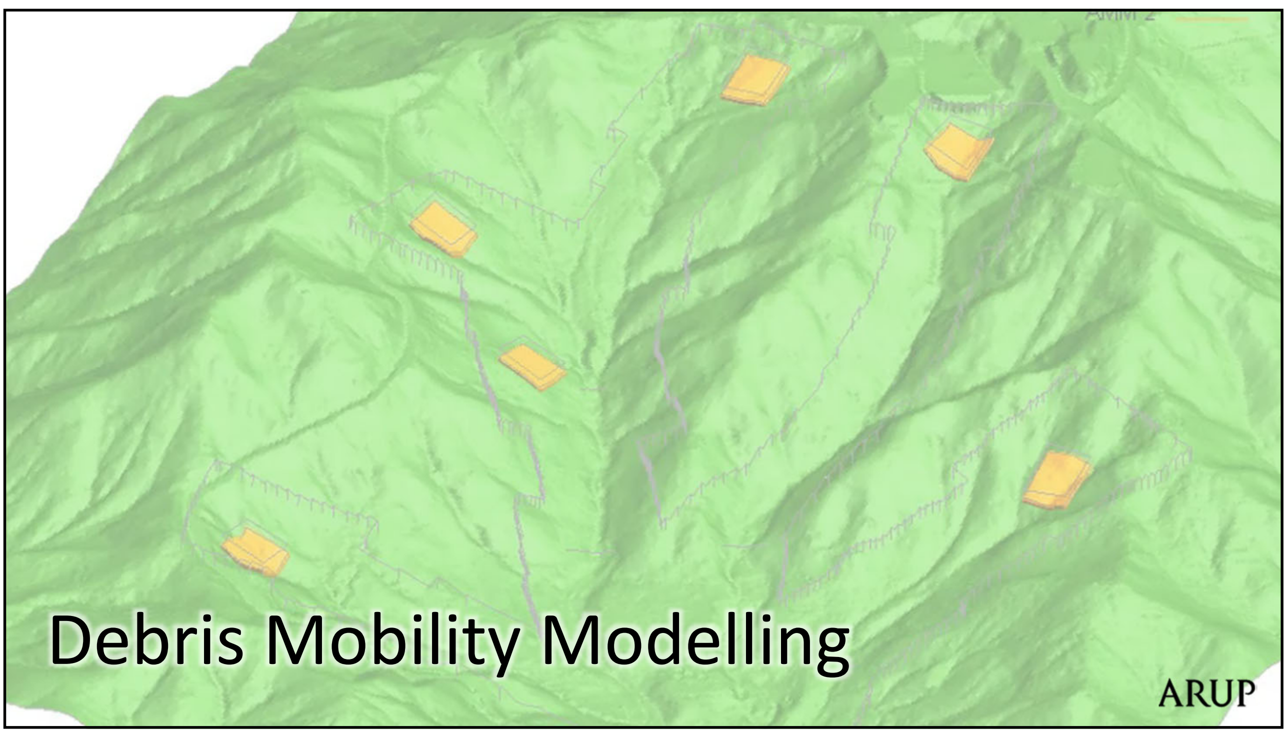
2016 - current



Engineering Application Perspective

Research → Validation → Adopt in Real Work


LS-DYNA Capabilities
Debris Mobility Modelling
1
Rock Fall
2
Interaction between the flexible barrier and the landslide debris
3
Energy Balance
4
Optimisation in Design of Flexible and Rigid Barriers
5
ALC Barrier 230cu.m - Energy vs. Time
Debris injection starts @ 2.25s
Time (Sec)
Design Debris Volume
ARUP

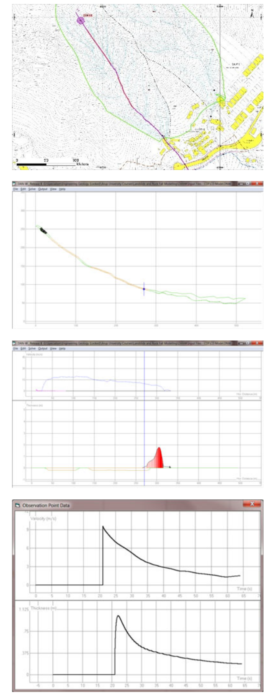

Debris Mobility Modelling
ARUP

Conventional Approach to **Debris Mobility Modelling**

GIS Flow Analysis

DAN/W or DMM Analysis
(2D/pseudo-3D analysis)

Export of key observation point data (debris volume passing, thickness and velocity) for subsequent design and checking using other tools



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Conventional Approach to **Debris Mobility Modelling**

- DAN-W or DMM has the following limitations in debris mobility…

No interaction between the debris from multiple source areas

Blockage effect of structural elements cannot be simulated

No areal extent of deposition and no debris thickness contour can be obtained.

Bifurcation of debris trails cannot be modelled

Effective but very subjective in some aspects of the analysis, especially the assignment of channel shape and width

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Conventional Approach to **Design of Structural Countermeasures**

1
- Debris mobility modelling carried out separately.

2
- Structural analyses of barriers carried out separately.

Problem
- Could not realistically account for the dynamic debris-barrier interaction

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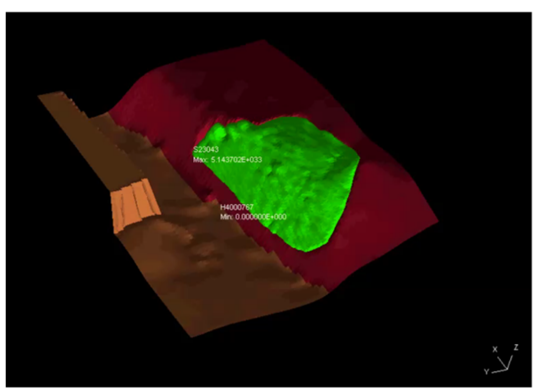
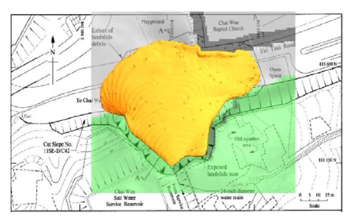
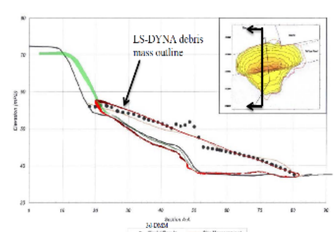
Open Hillslope Landslide (OHL)

- Pure frictional rheology model adopted in the LS-DYNA simulation was proven to be successful in predicting debris slide. Example of Fei Tsui Road Landslide occurred in Hong Kong in Year 1995



Fei Tsui Road Landslide LS-DYNA Animation





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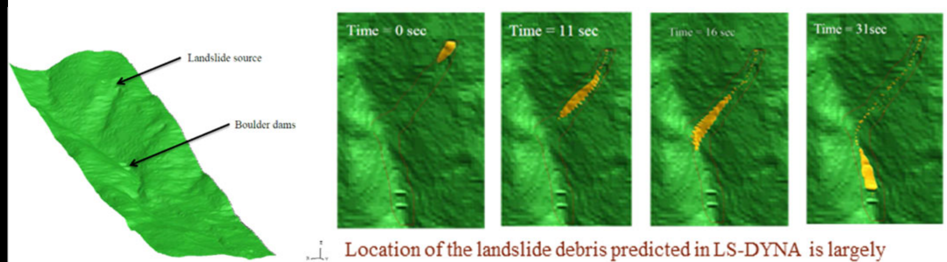
Channelised Debris Flow (CDF)

- Introduction of Voellmy rheology by modifying the program codes to suit typical debris flow hazards in Hong Kong.
- Example of Kwun Yam Shan Landslide occurred in Hong Kong in 2005



Location of the landslide debris predicted in LS-DYNA is largely comparable to GEO 3D-DMM for Kwun Yam Shan Landslide

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Make changes to program codes

- Tailor made to make changes to codes for different applications according to client's needs

Additional Voellmy resistance term at the ALE solid / rigid shell interface

$$T = A_i\left[\gamma H_i\left(\cos\alpha + \frac{a_c}{g}\right)\tan\phi + \gamma\frac{v_i^2}{\xi}\right]$$

In the interaction input for ALE solid –
"*CONSTRAINED_LAGRANGE_IN_SOLID"
an extra "damping" term is added to for (γ/ ξ) which applies an resistance to the interface based on v^2

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Calibration of Landslides in Hong Kong and overseas

- Debris mobility modelling using LS-DYNA have been calibrated against several well-documented landslide in Hong Kong and overseas to ensure program appropriateness and robustness in debris mobility modelling

HONG KONG

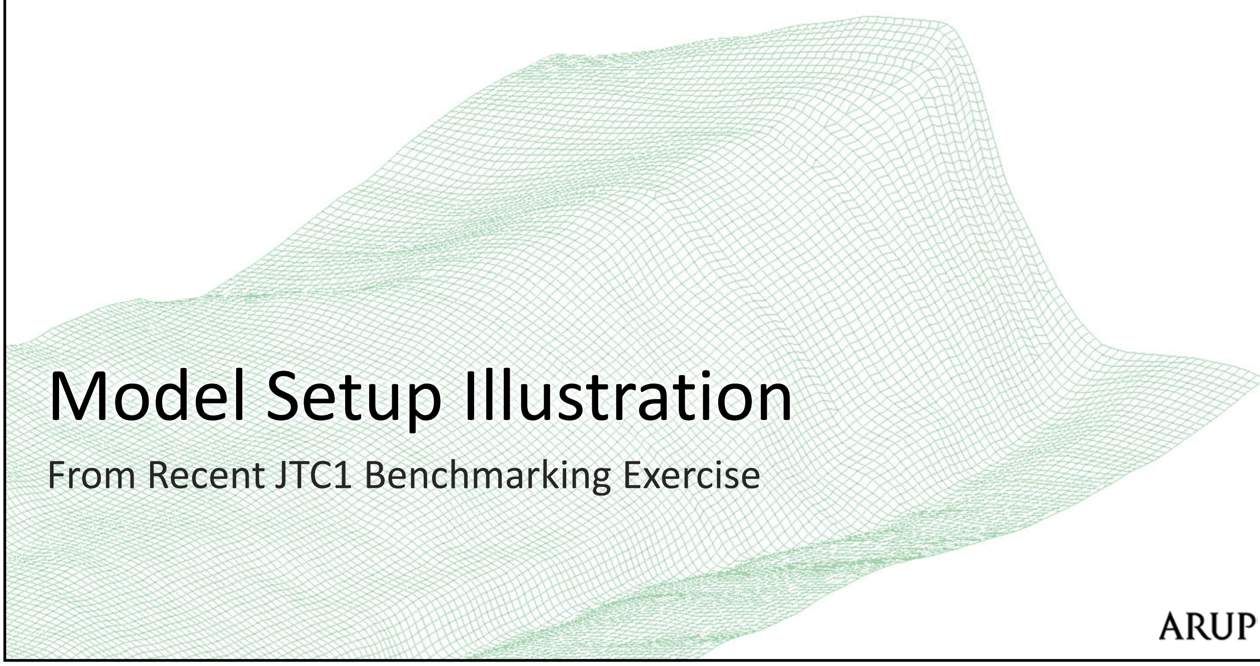
- Yu Tung Road landslide on 7th June 2008
- Kwun Yam Shan landslide on 22nd August 2005
- Sham Tseng San Tsuen debris flow on 23rd August 1999
- Fei Tsui Road landslide on 13th August 1995

OVERSEAS

- USGS laboratory flume tests reported by Iverson et al. (2004)
- Rock fall tests by Volkwein (2004)
- Illgraben flexible barrier field tests

- Pre-approved 3D numerical software for debris mobility by GEO in March 2016

ARUP

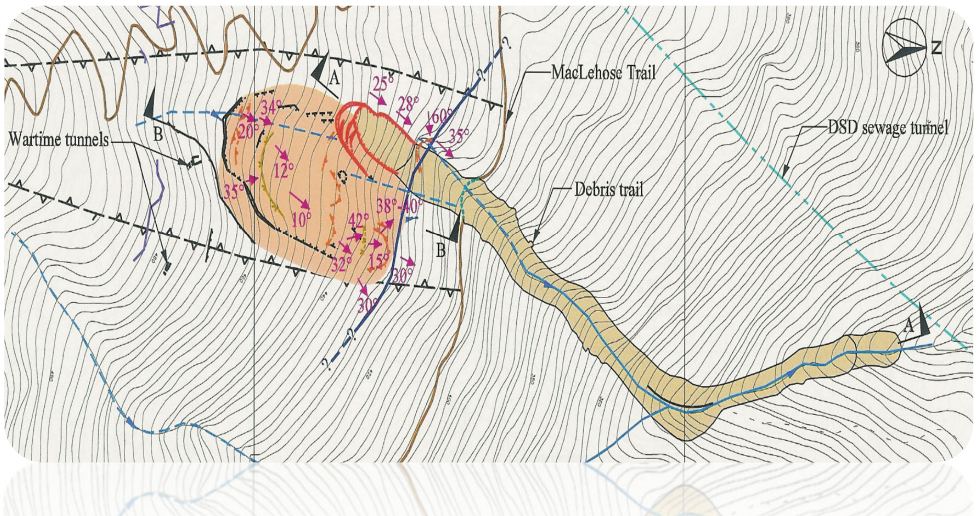


Model Setup Illustration

From Recent JTC1 Benchmarking Exercise

ARUP

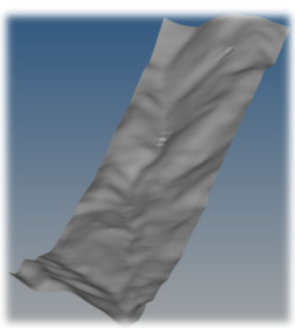
A historical landslide catchment in Hong Kong

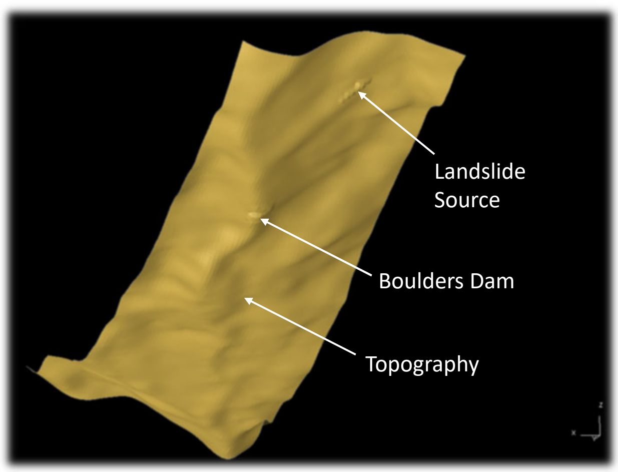


ARUP

Model Setup – The Topography

- ➢ Modelled by rigid shell elements
- ➢ Resolution = 5m x 5m
- ➢ No. of elements = 11,550

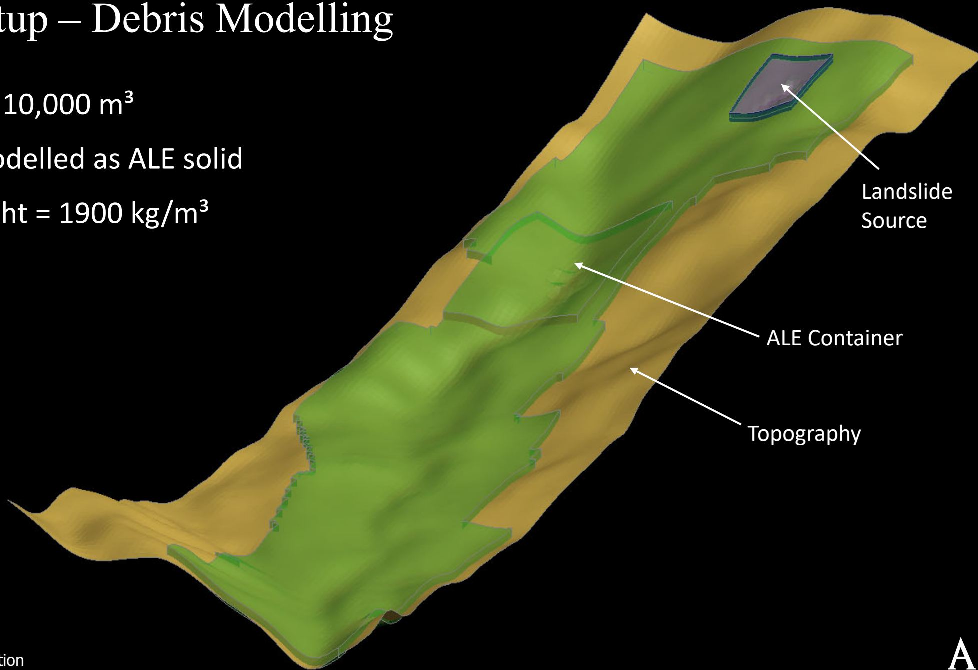




ARUP

Model Setup – Debris Modelling

- Volume = 10,000 m^3
- Debris modelled as ALE solid
- Unit Weight = 1900 kg/m^3

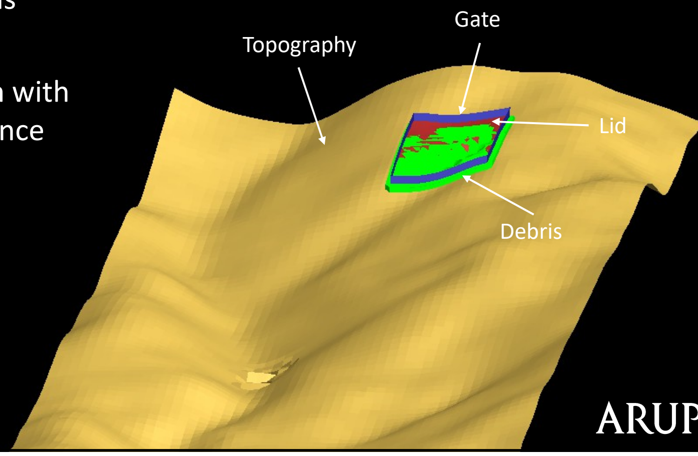


Model Setup Illustration

ARUP

Model Setup – Gravity Initialisation

- Debris mass initialised at source location by applying gravity load within first 2 seconds
- An artificial rigid tube and lid, acting as the gate, to confine and restrict the debris mass movement during initialization
- The gate has very low contact friction with the debris mass to minimize disturbance



Model Setup Illustration

ARUP

Model Setup – Gravity Initialisation

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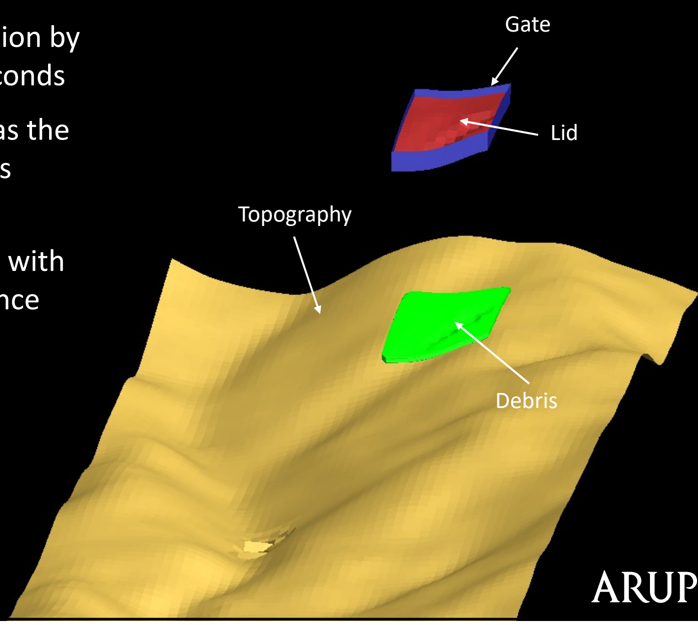


Model Setup Illustration

ARUP

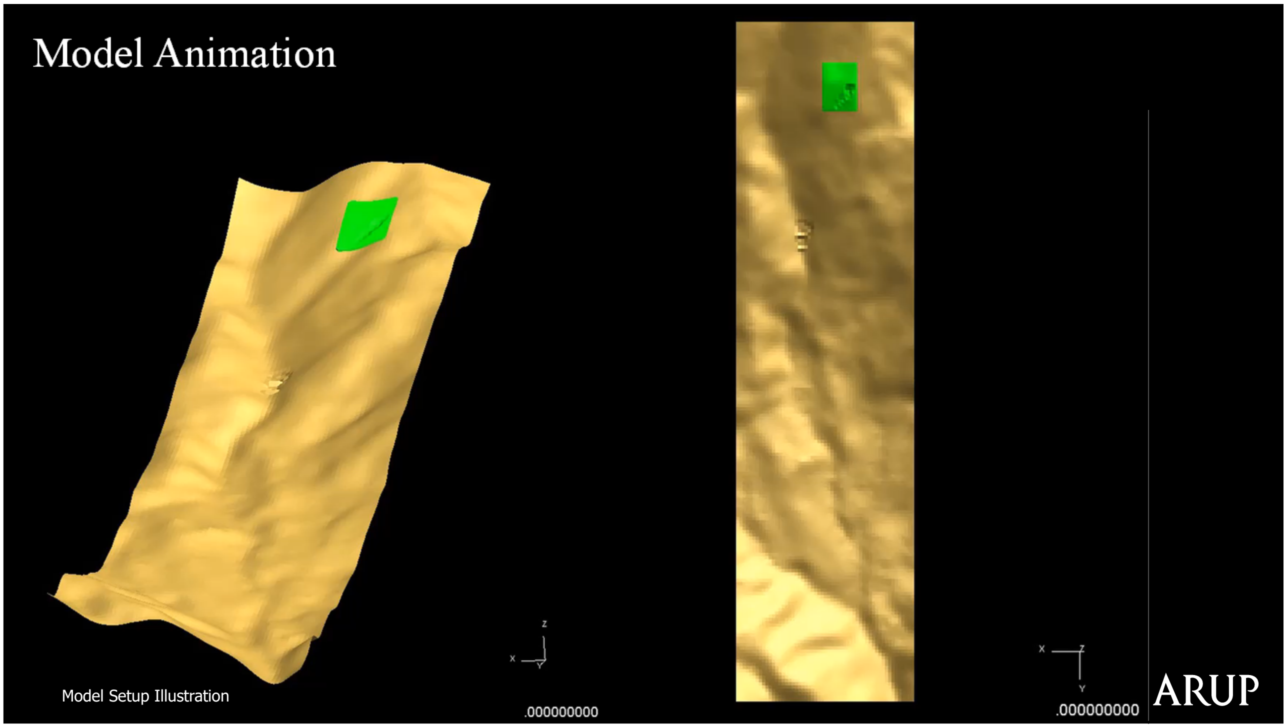
Setup – Debris Mass and Basal Friction

- Debris mass movement captured at regular 0.5s interval

Rheology	Material Property	Adopted input parameters	Remarks
Voellmy	Internal friction angle, φ_i	15°	Arup (2014)
	Basal friction angle, φ_b	8°	GEO TGN 29 (Adverse Site Setting Parameters)
	Turbulence coefficient	500 m/s²	

Model Setup Illustration

ARUP


Model Animation
Model Setup Illustration
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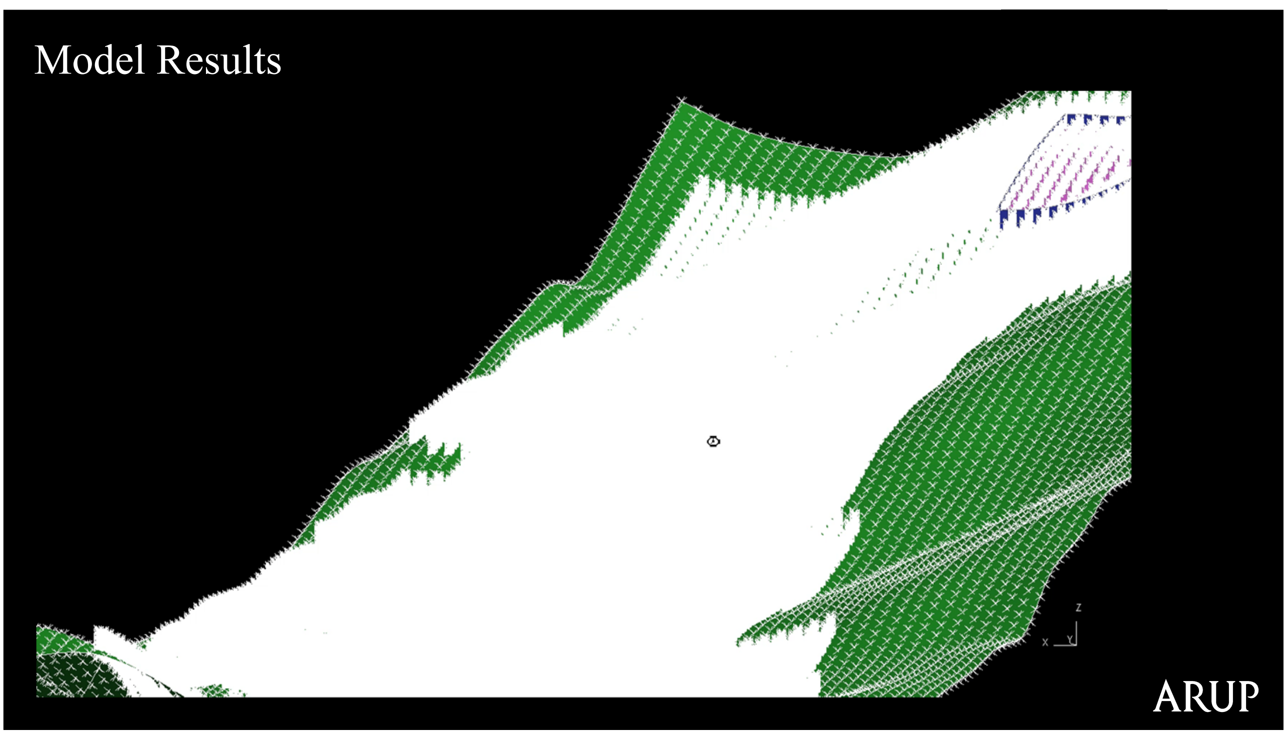
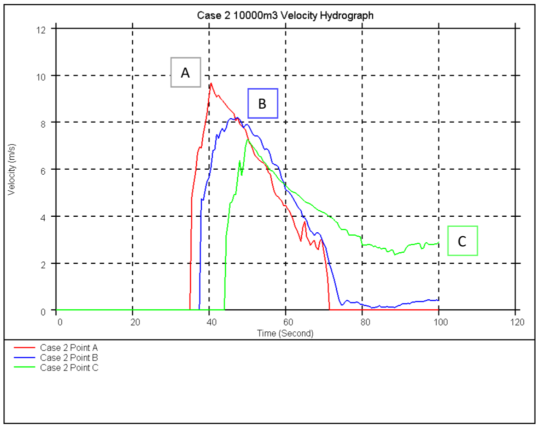
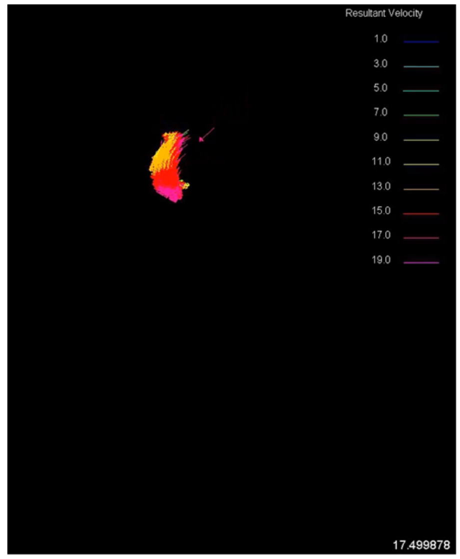

Model Results
ARUP

Model Results – Velocity Hydrograph

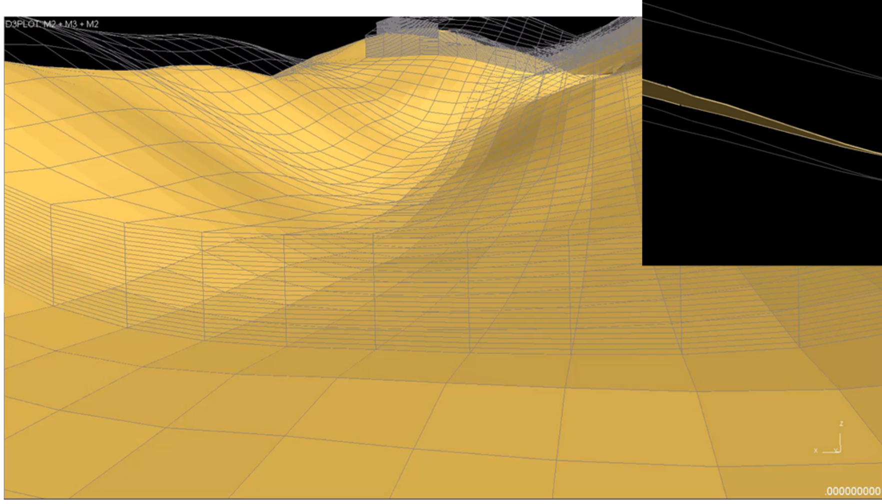


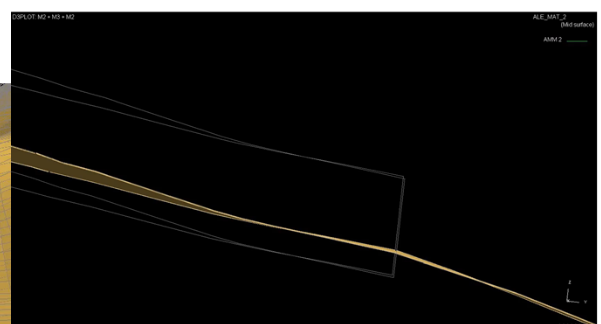


	Point A	Point B	Point C
Maximum Velocity (m/s)	**9.7**	**8.2**	**7.3**
Time Recorded (s)*	**40.5**	**47.5**	**50.0**

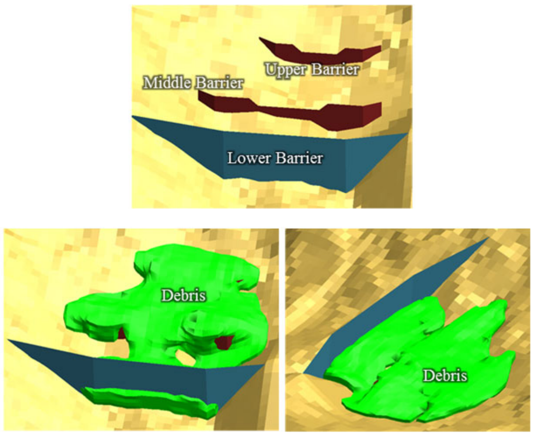
***Debris are allowed to slide downslope at t=2s**

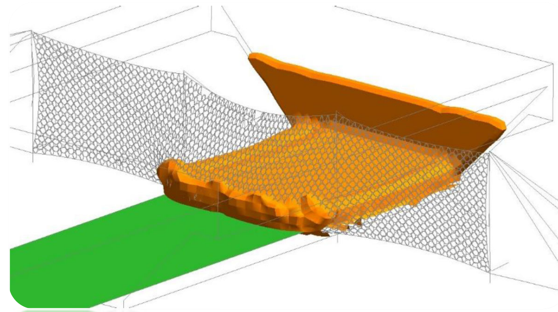
Model Animation – Debris Thickness at Point A





Possible Mitigation Measures





Debris-flexible barrier interaction using LS-DYNA

Model Setup Illustration

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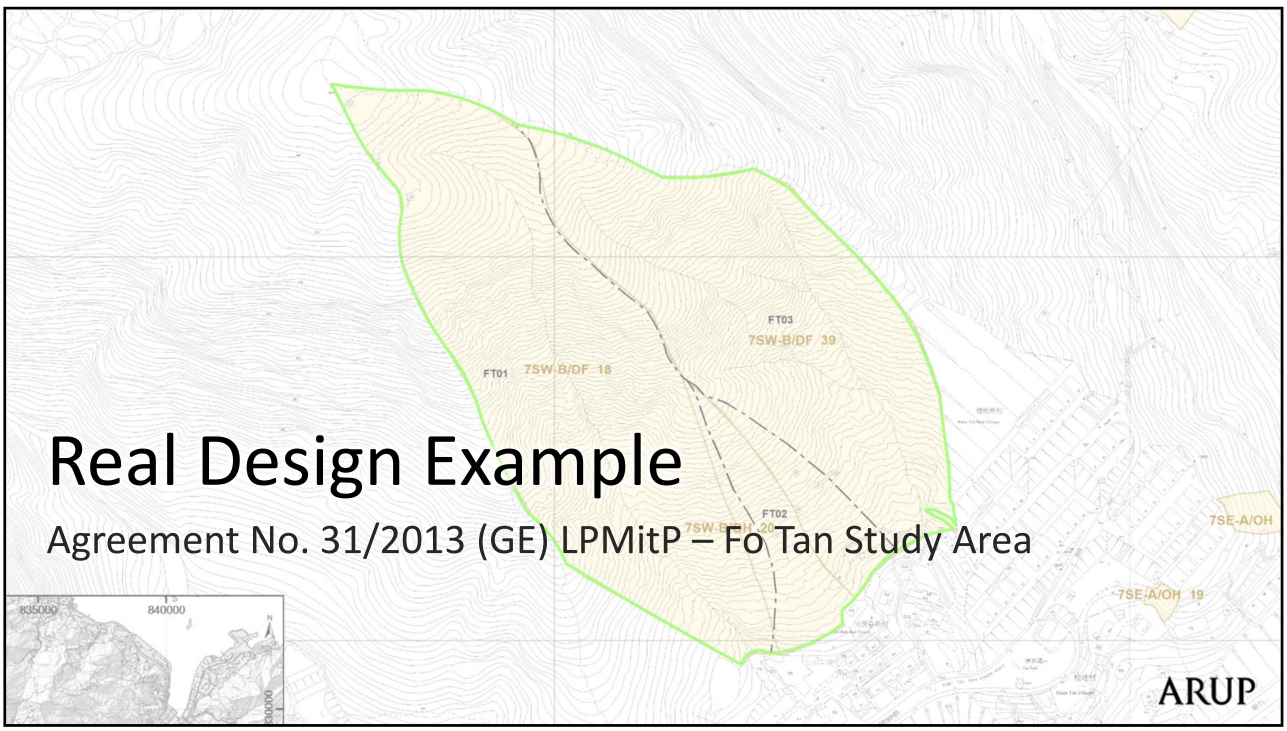

Real Design Example

Agreement No. 31/2013 (GE) LPMitP – Fo Tan Study Area

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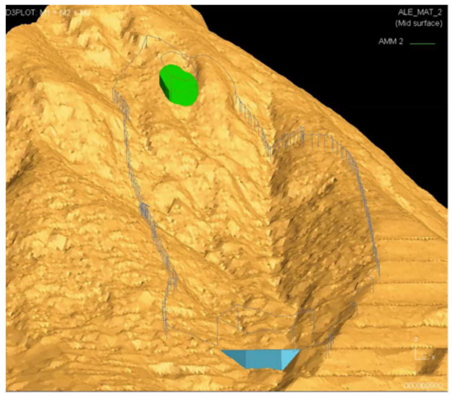
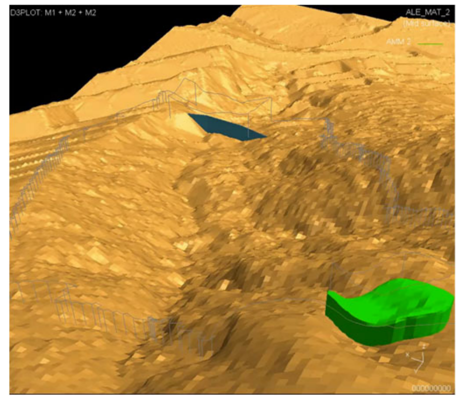
Agreement No. 31/2013 (GE) LPMitP –

Fo Tan Study Area

Fo Tan Design Option 1

- A 5.0m high rigid barrier
- 2 rows of baffles
- Maintenance stairways





Catchment No. FT03

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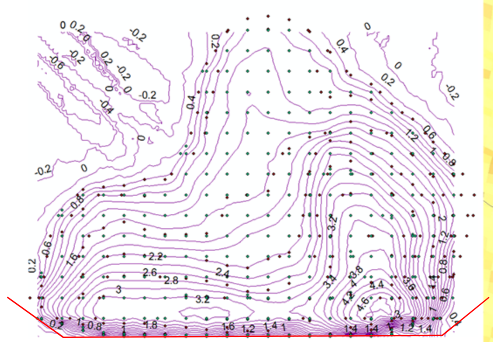
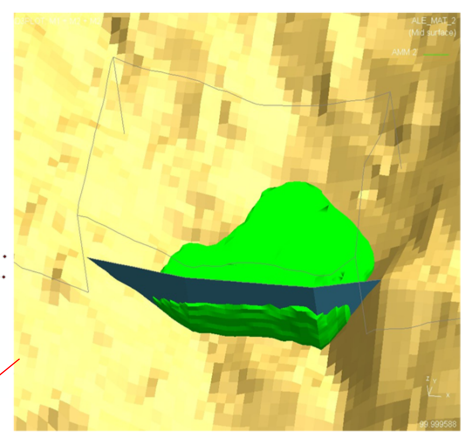
Agreement No. 31/2013 (GE) LPMitP –

Fo Tan Study Area

Fo Tan Design Option 1

Debris Thickness Contour (max. 4.6 m)





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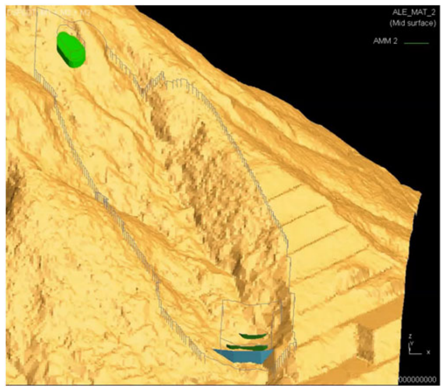
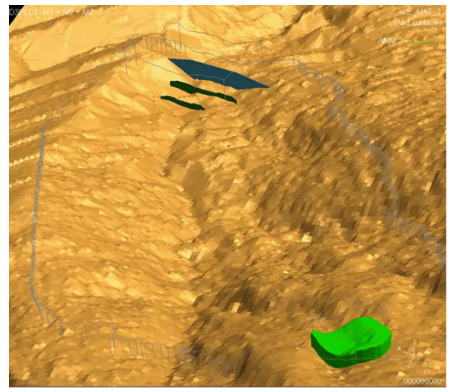
Agreement No. 31/2013 (GE) LPMitP –

Fo Tan Study Area

Fo Tan Design Option 2

- Two 2.5m high intermediate rigid barriers
- A 2.5m high terminal rigid barrier
- Baffles behind each barrier
- Maintenance stairways





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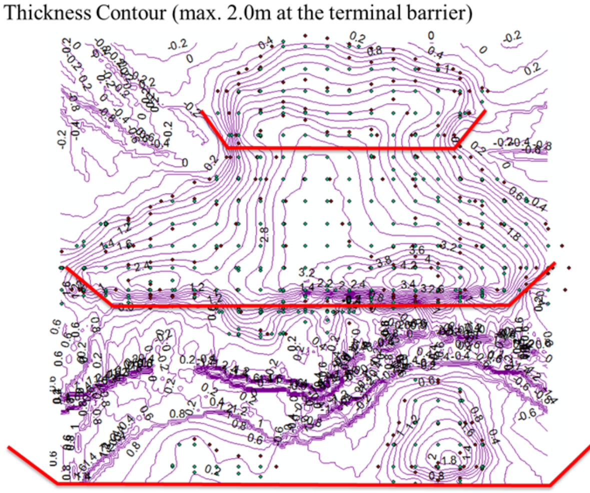
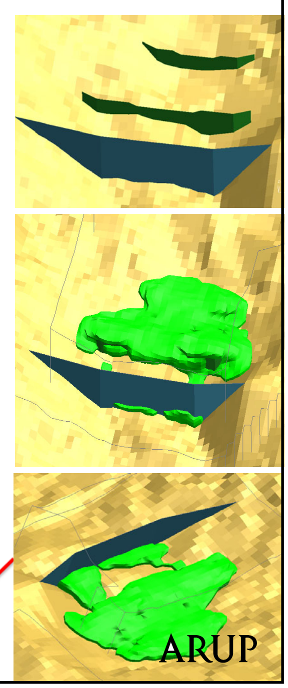
Agreement No. 31/2013 (GE) LPMitP –

Fo Tan Study Area

Fo Tan Design Option 2

Debris Thickness Contour (max. 2.0m at the terminal barrier)





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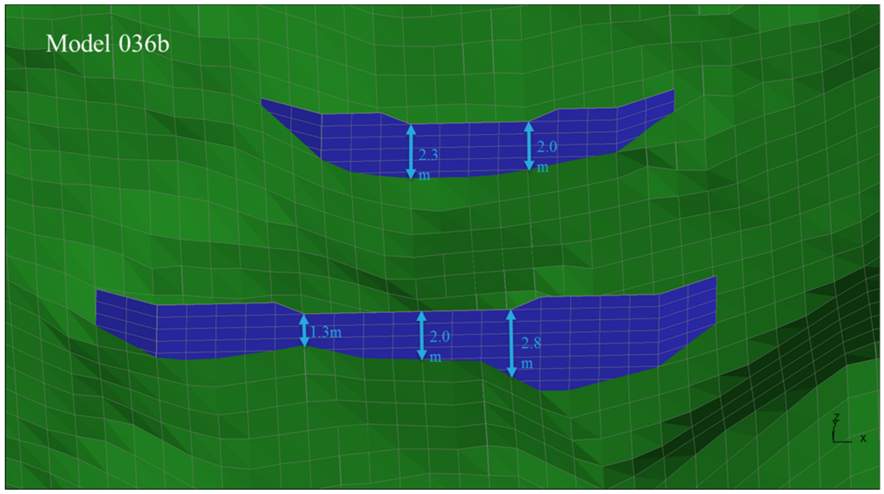
Agreement No. 31/2013 (GE) LPMitP –

Fo Tan Study Area

Optimisation of rigid barrier design in terms of dimension and configuration based on topography from LiDAR data



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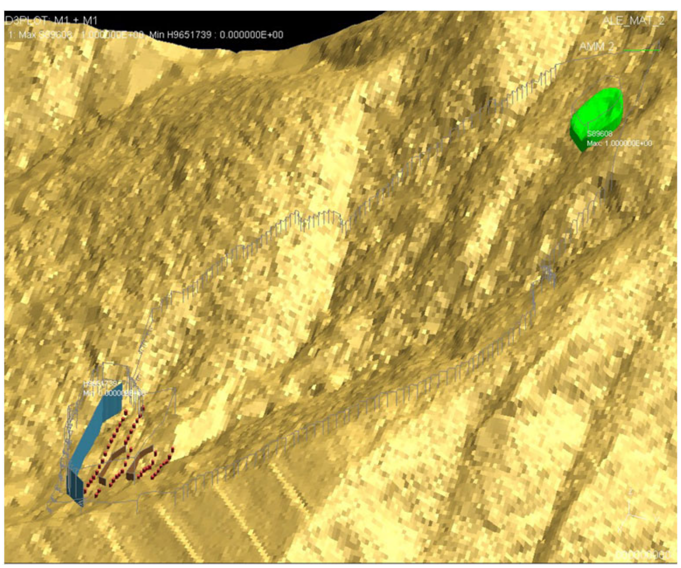
Multiple Barriers with Baffles



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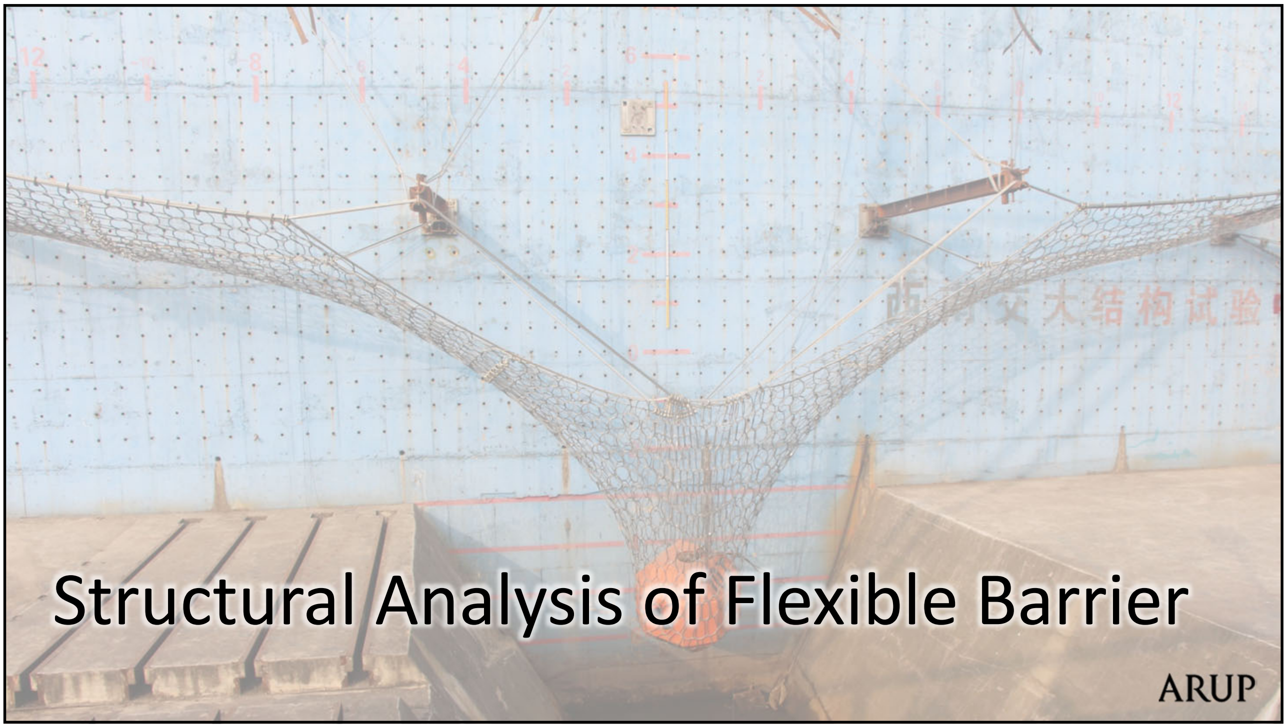
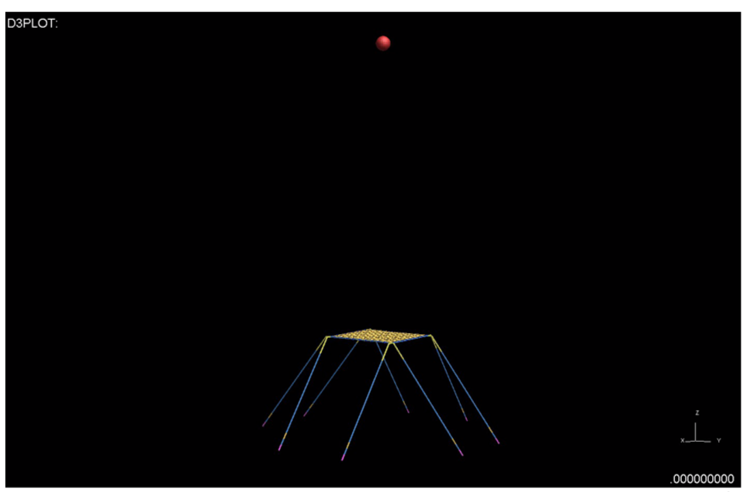


Structural Analysis of Flexible Barrier

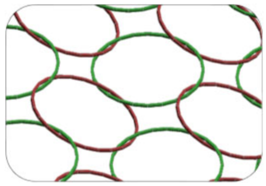
LS-DYNA is able to predict the concrete ball displacement and energy very closely matched with the test results demonstrated by Volkwein (2004)



ARUP

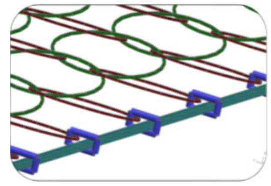
Structural Analysis of Flexible Barrier

All structural components including the cable, shackles, brake rings and ring net were modelled using beam elements.

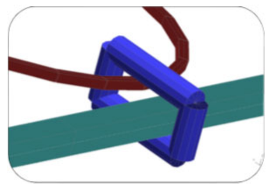


Ring Net

Connection



Cable



Shackles

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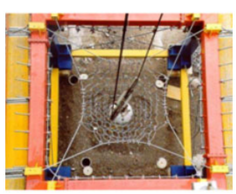
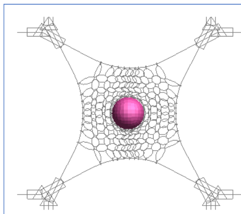
Structural Analysis of Flexible Barrier

Deformation matched.



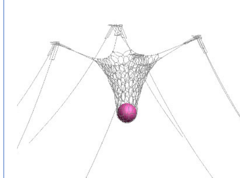
REAL TEST

Plan view of final position of the concrete ball



LS-DYNA Simulation

Plan view of final position of the concrete ball



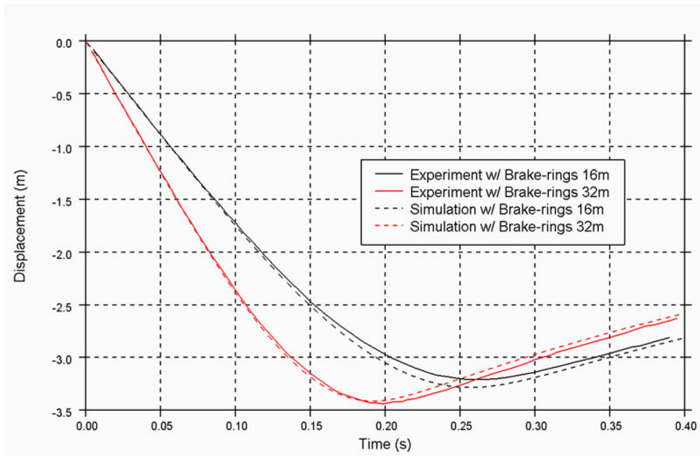
LS-DYNA Simulation

Deformation of the flexible barrier in LS-DYNA

ARUP

Structural Analysis of Flexible Barrier

Results and comparison with the test results on vertical position of the concrete ball and tension force developed on the steel cables

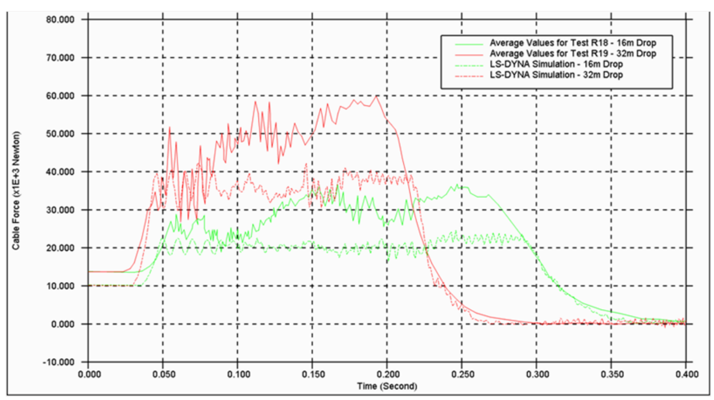


Displacement-time curves for LS-DYNA simulation and experimental results from Volkwein.

ARUP

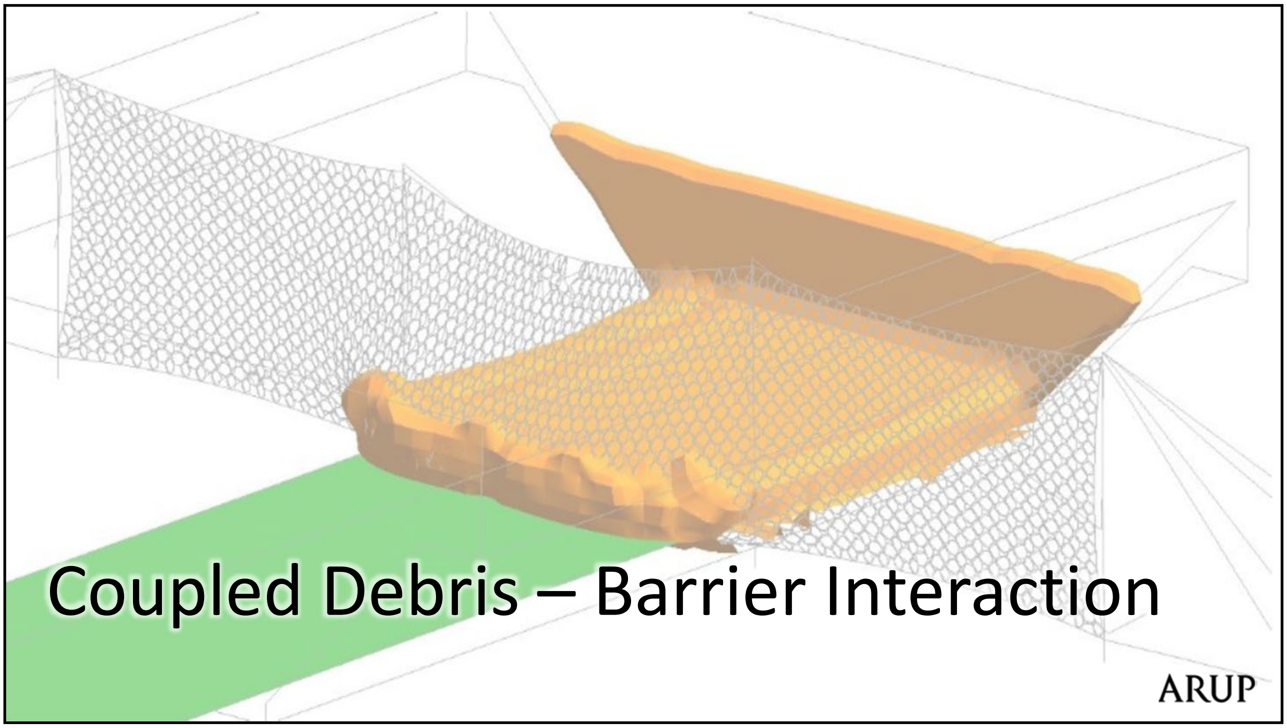
Structural Analysis of Flexible Barrier

Results and comparison with the test results on vertical position of the concrete ball and tension force developed on the steel cables



Cable force vs. time curves for LS-DYNA simulation and experimental results from Volkwein

ARUP

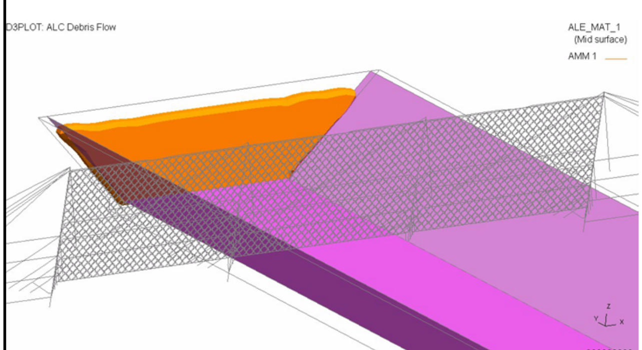


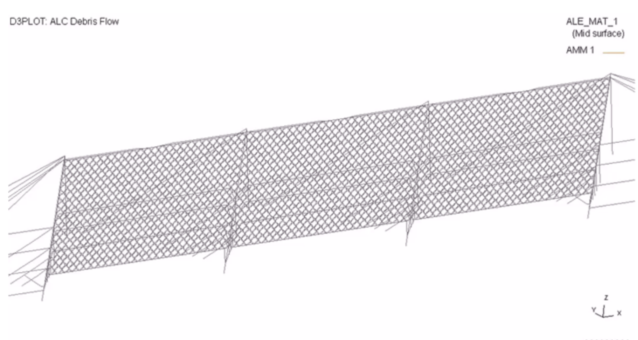
Coupled Debris – Barrier Interaction

ARUP

Soil-Flexible Barrier Interaction

- With same modelling technique, the interaction between the debris flow and flexible barrier can be analysed. Force, velocity, energy vs time can be obtained.





Validation

- Coupled analysis between the Rockfall/Debris and Debris Retaining/Resisting Structures using LS-DYNA have been validated against several well-documented landslide in Hong Kong and overseas to ensure program appropriateness and robustness.

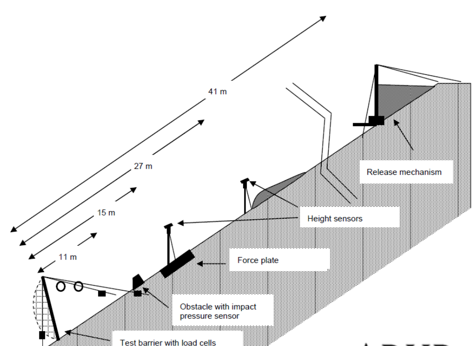
> - Flexible Barrier Field Test in Illgraben, Switzerland
> - Shallow Landslide Full-scale Field Test on Flexible Barrier in Veltheim, Switzerland
> - Ship Impact Assessment on Pile Structural Foundations for Viaducts / Bridges
> - HKUST Centrifuge Modelling of Debris Impact on Barriers
>
> **Validation Cases**

- Use of LS-DYNA for the application of coupled analysis of interaction between rock/boulder/debris and debris-resisting barrier structures is approved by BD and can be used in all private / public works in 2018

The Veltheim Field Test Model

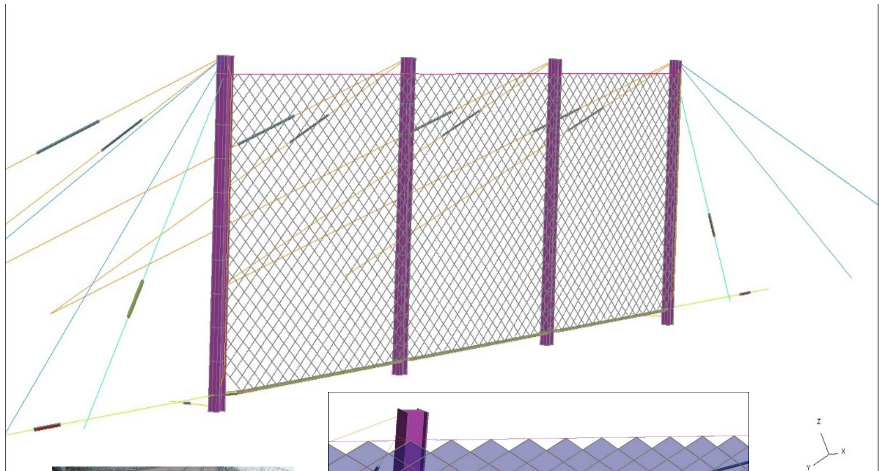
Background

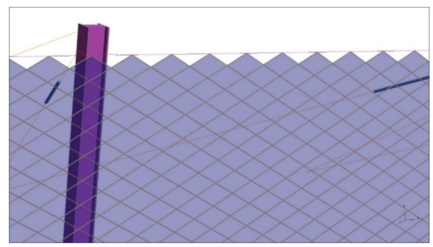
- A full-scale test carried out in Veltheim, Switzerland using Geobrugg barriers.
- Release of artificially mixed debris material along a 40 m, 30° flume



The Veltheim Field Test Model

Model Setup – Flexible Barrier





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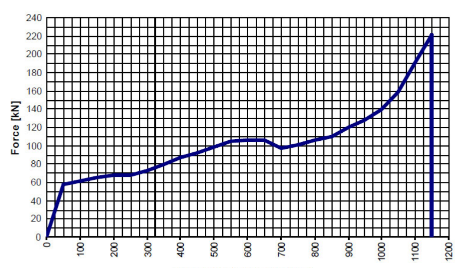
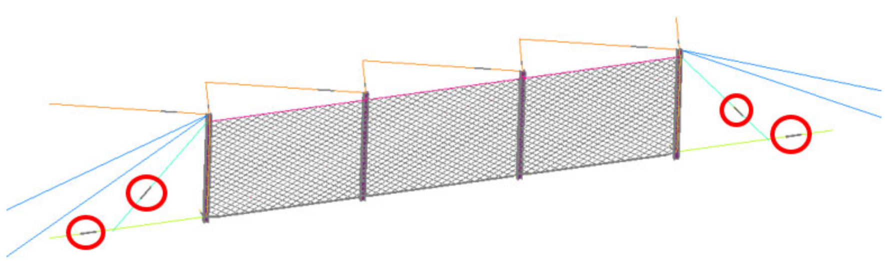
The Veltheim Field Test Model

Model Setup – brake element

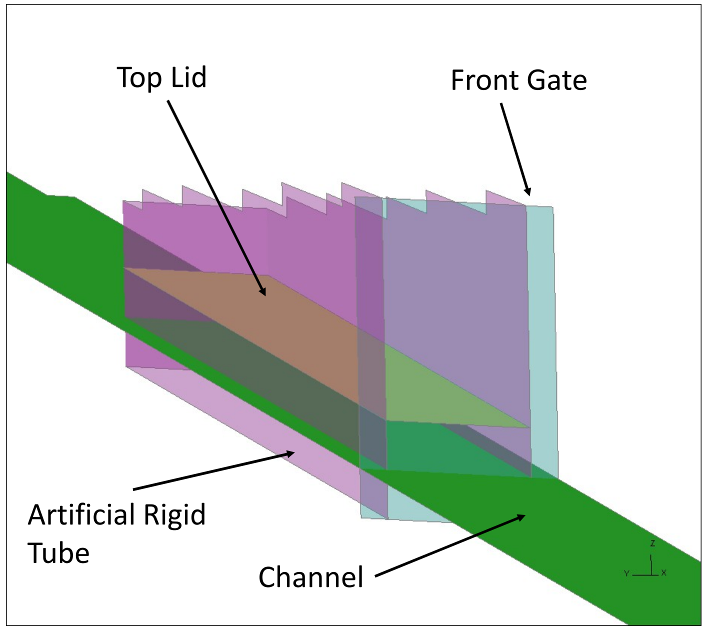




ARUP

The Veltheim Field Test Model

Model Setup – Debris Container



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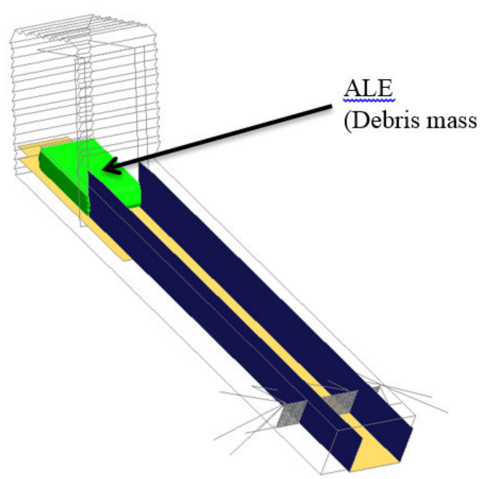
The Veltheim Field Test Model

Model Setup – Topography



- Channel Width = 8 m
- Length to barrier = 41 m
- Inclination = 30°
- Debris Density = 2085 kg/m³
- Contact Friction between channel base and debris = 25°
- Contact Friction between channel side and debris = 25°
- Internal Friction of debris= 20°

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The Veltheim Field Test Model

Model Setup

- Internal Friction Angle = 15°
- Basal Friction Angle = 15°

Action	Timesteps	Location of Debris
Gravity initialisation	0 – 1.0 s	Remained within container
Gate opening to 1 m above topography	1.0 – 2.0 s	Debris started to slide downward
Gate remained open	1.5 – 100.0 s	All debris flew out of the container

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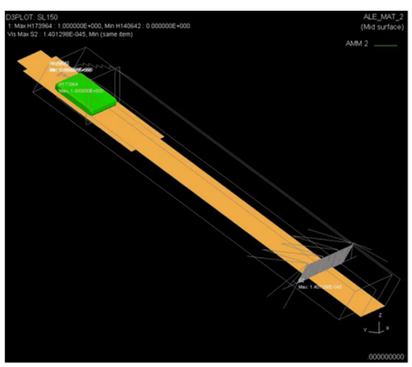
The Veltheim Field Test Model

Model Result



- Debris velocity closely resembled actual scenario

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The Veltheim Field Test Model

Model Result

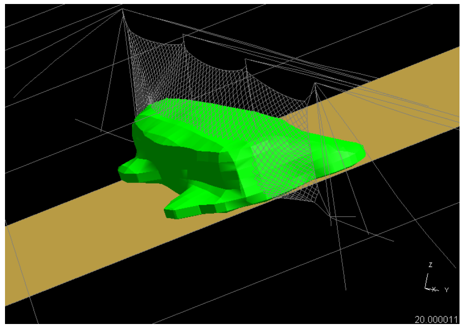
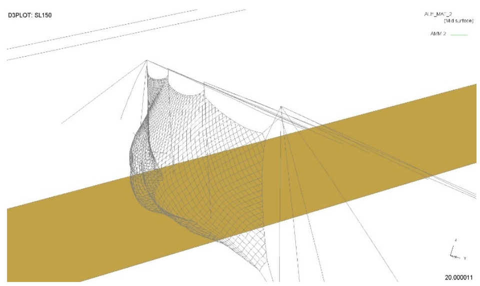
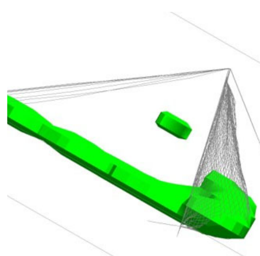




Fig. 8: Barrier after release 1.

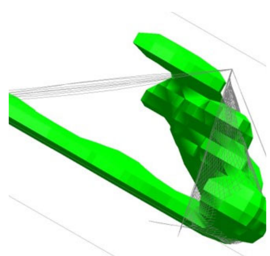
The Veltheim Field Test Model

Model Result

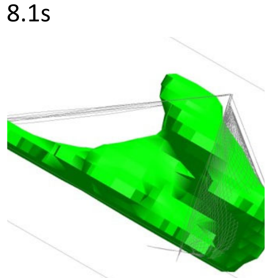
6.5s



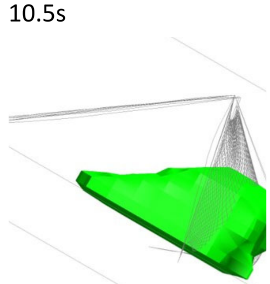
7.2s



8.1s



10.5s



The Veltheim Field Test Model

Debris Location and Time

	Release	Post 1	Post 2	Post 3
x (m) distance from storage tank	0	11	21	31
t (s) (Actual Test)	0	1.54	2.82	3.8
t (s) (LS-DYNA)	0	1.8	2.8	3.5
Velocity (m/s) (Actual Test)		7.1	7.8	10.2
Velocity (m/s) (LS-DYNA)		6.1	10.0	14.3

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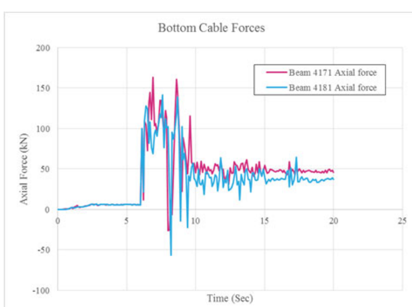
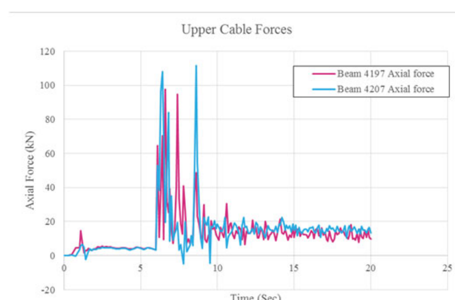
The Veltheim Field Test Model

Cable Forces

	Upper Cable	Lower Cable	Upslope Cable
Cable Forces in Actual Test (kN)	40	74	42
Cable Forces in LS-DYNA (kN)	111	163	65





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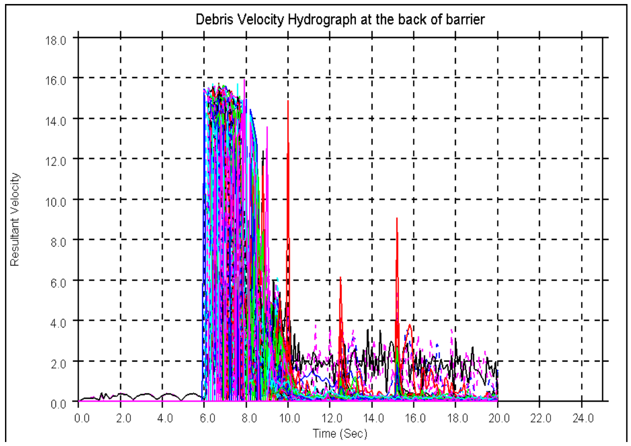
The Veltheim Field Test Model

Velocity behind the barrier



- The maximum velocities of debris recorded at the back of the barrier were approximately 15 to 16 m/s, which was comparable to the actual test results. The impact duration was approximately 2 sec.

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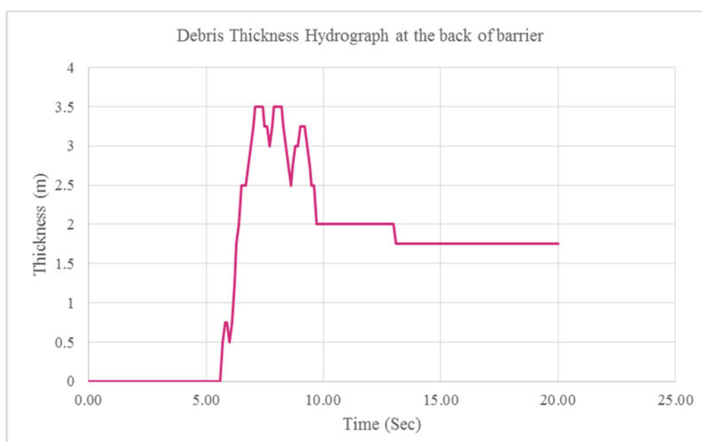
The Veltheim Field Test Model

Debris Thickness behind the barrier



- The debris front reached the barrier and the debris thickness increased to 3.5 m in approximately 1.5 sec.
- After approximately 4 sec after impact the debris became static with a thickness of 1.75 m

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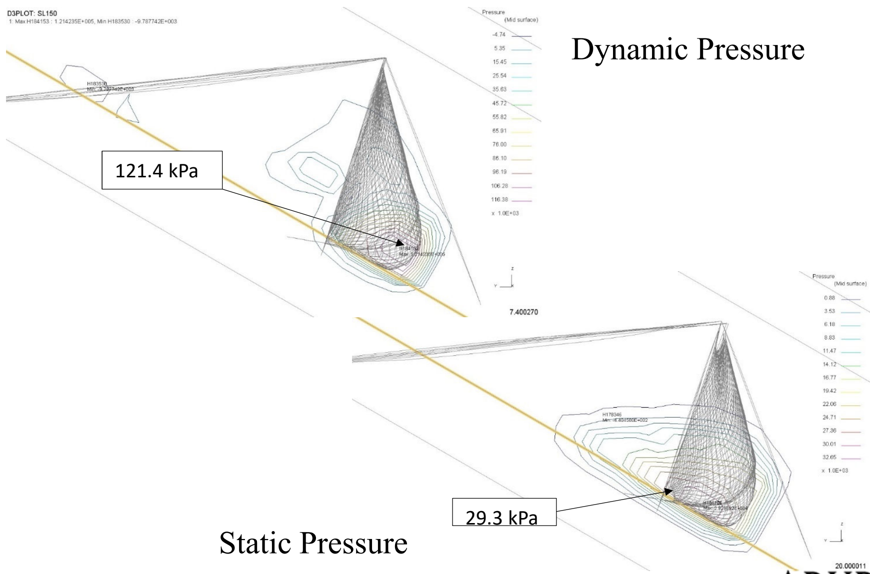
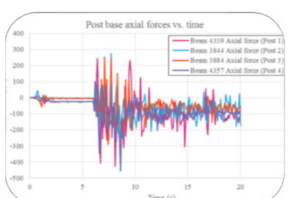
The Veltheim Field Test Model

Dynamic impact pressure and static pressure

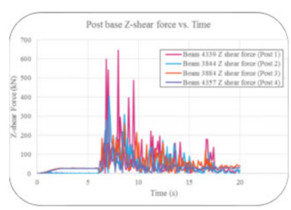


The Veltheim Field Test Model

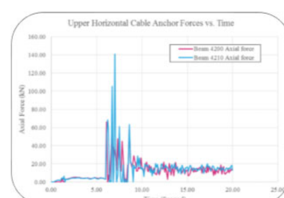
Plus more results….



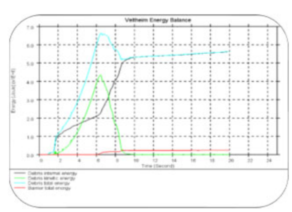
Post Base Axial Force



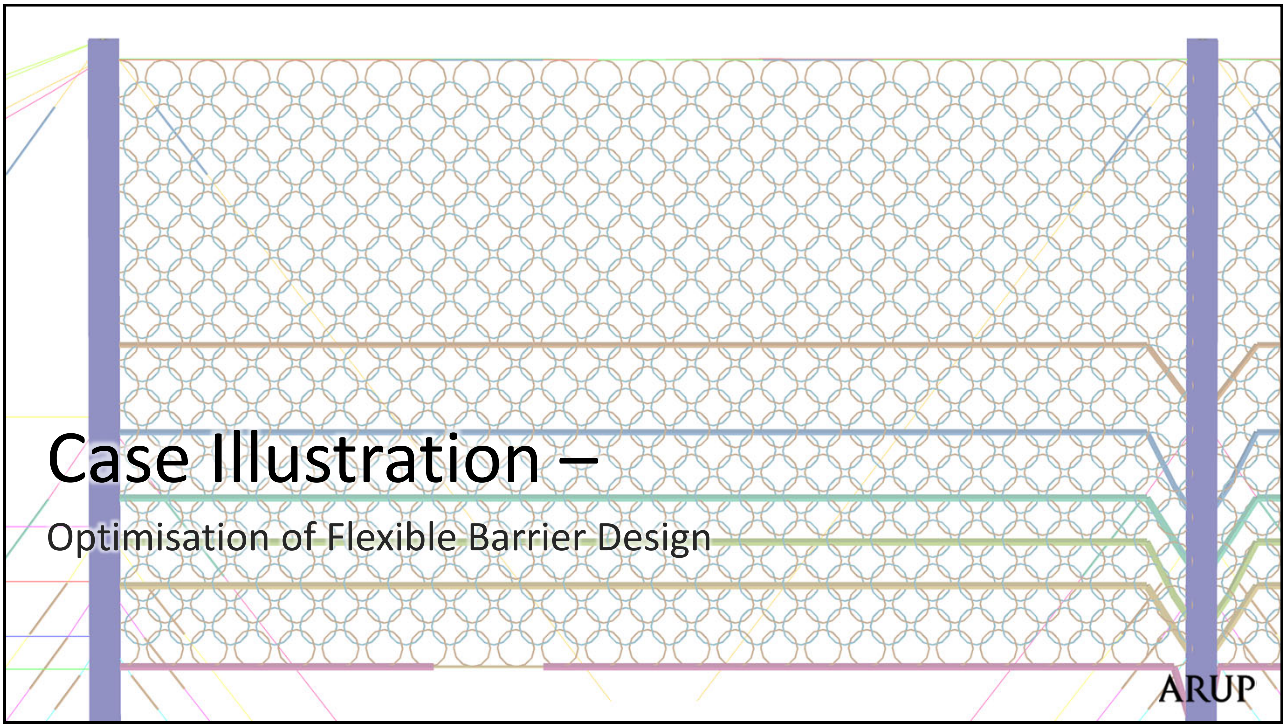
Post Base Shear Force



Horizontal Cable Anchor Force



Energy Balance

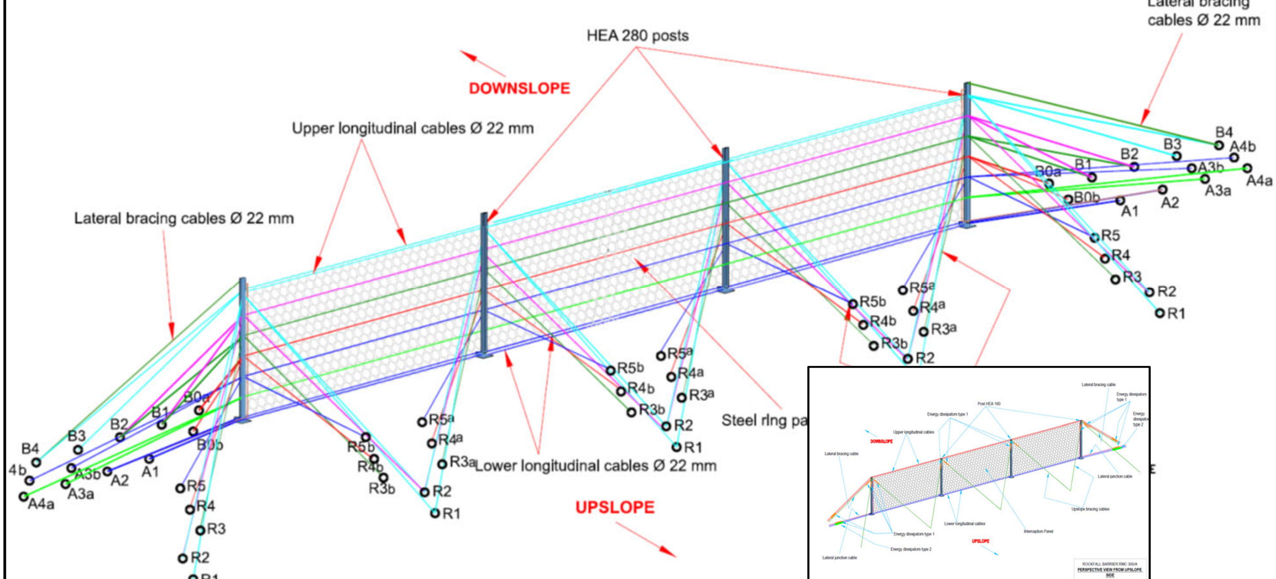


Case Illustration –

Optimisation of Flexible Barrier Design

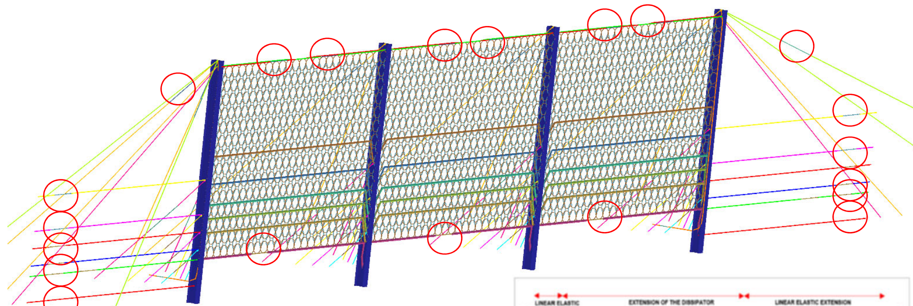
ARUP

Details of the Barrier

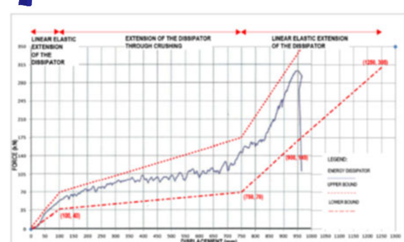


Brake Element (Energy Dissipators)

- Maximum load allowed per brake element = 305kN
- Maximum elongation at 305kN = 1250mm



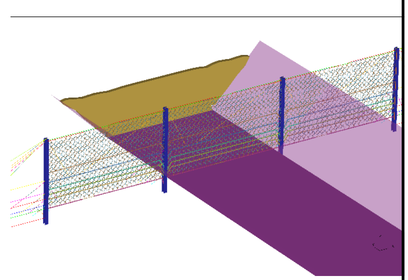
Location of brake elements along horizontal cable ropes

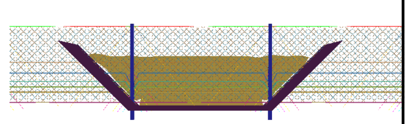


Load-deformation Curve

Methodology

- The flexible barrier is placed at 10 m away from debris source
- Apply gravity to the barrier and let it settle down
- Inject ~1m thick debris at specified speed (base case = 11m/s) and specified duration
- Record deformation and structural forces during the simulation





Simulation in this Study –

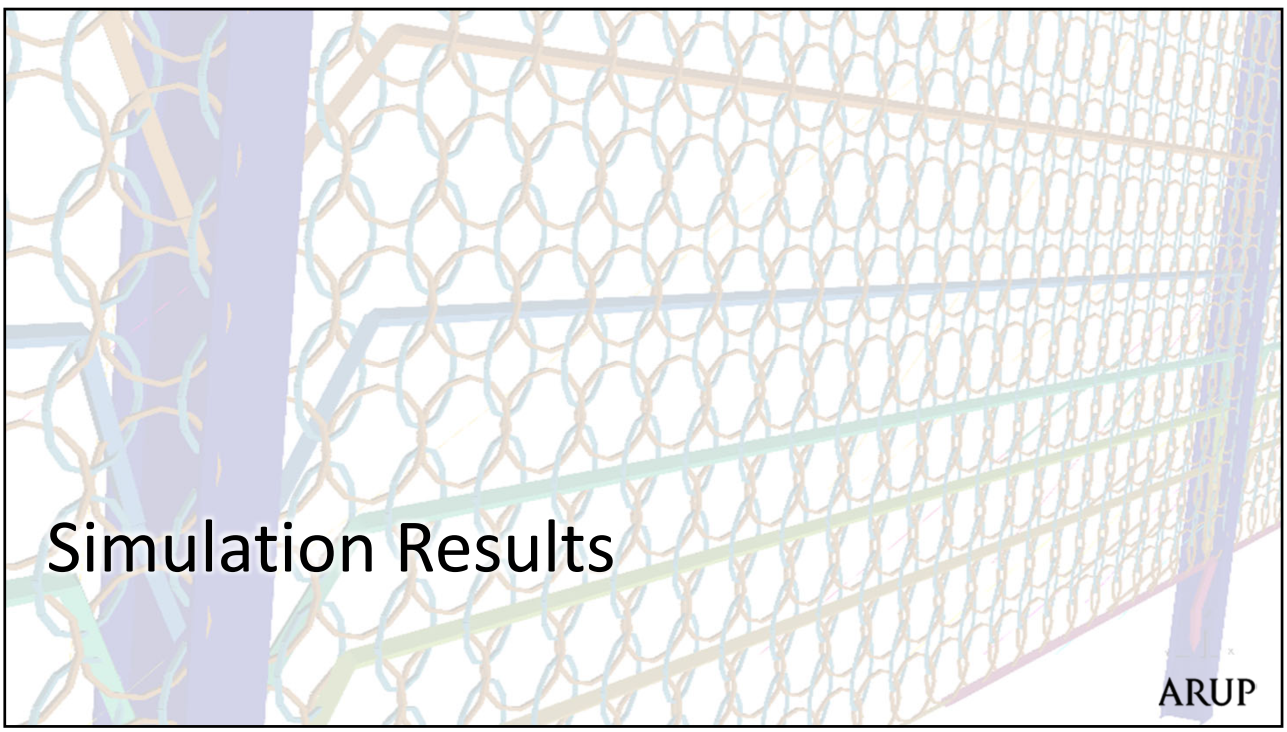
Simulation Strategy

1 **Base case** – 7 nos. layers of cables, 230 m³ debris with impacting velocity at 11m/s

2 **Sensitivity check** of base case – increasing volume to overflow, and increasing impacting velocity to 15 m/s

3 **Parametric study** – reducing the no. of layers of cables

Bulging Distance **Residual Height** **Cable Forces**
Brake Element Forces **Energy Balance** **Etc…**



Simulation Results

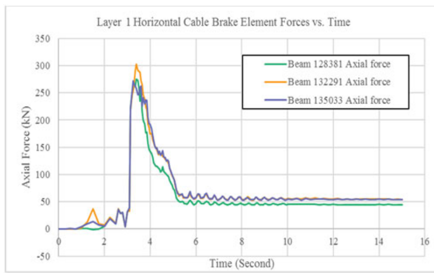
Simulation Results

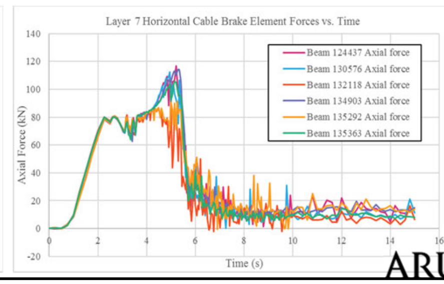
Base Case

7 nos. layers of cables, 230 m^3 debris with impacting velocity at 11m/s

Brake element at horizontal cables

Layers	Number of Cables	Allowable tension force based on acceptance criteria (kN)	Recorded maximum tension force (kN)	Utilisation of brake elements (%)
Layer 1	6	1800	303	17
Layer 2	6	1800	304	17
Layer 3	6	1800	367	20
Layer 4	6	1800	347	19
Layer 5	4	1200	243	20
Layer 6	4	1200	228	19
Layer 7	2	600	117	20





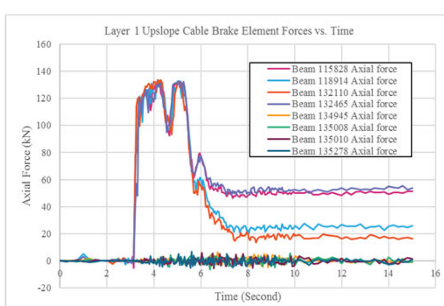
Simulation Results

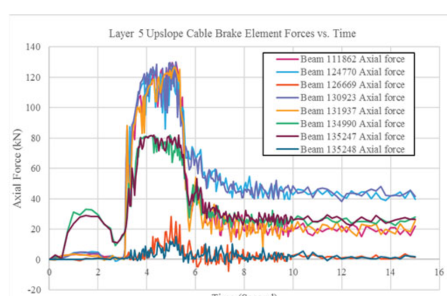
Base Case

7 nos. layers of cables, 230 m^3 debris with impacting velocity at 11m/s

Brake element at upslope cables

Layers	Number of Cables	Allowable tension force based on acceptance criteria (kN)	Recorded maximum tension force (kN)	Utilisation of brake elements (%)
Layer 1	3	900	134	15
Layer 2	3	900	140	16
Layer 3	3	900	145	16
Layer 4	1	300	52	17
Layer 5	2	600	130	22



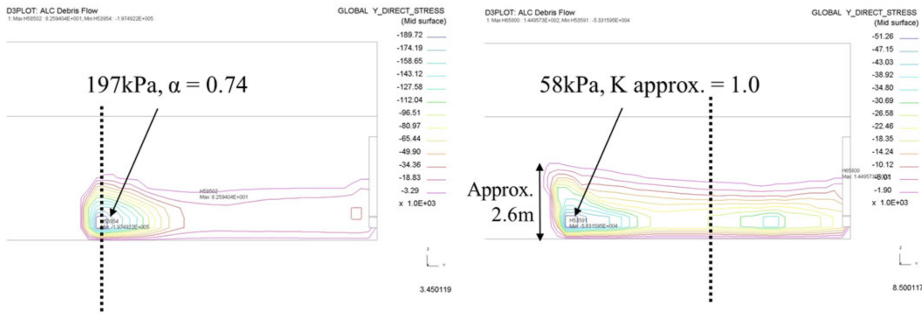


Simulation Results

Base Case

7 nos. layers of cables, 230 m^3 debris with impacting velocity at 11m/s

Debris pressure acting on the barrier



Impact pressure

Static pressure

$$p_d = \alpha \rho_d v^2 \quad \text{(B.1)}$$

where ρ_d = density of moving debris, taken to be 2,200 kg/m^3 as a minimum
v = velocity of moving debris hitting the barrier (m/s)
α = dynamic pressure coefficient, taken to be 2.0

$$p_s = K d \rho_s g \quad \text{(B.2)}$$

where K = coefficient of earth pressure, taken to be 1.0
d = depth below the upper surface of moving debris (m)
ρ_s = density of the deposited debris, taken to be 2,200 kg/m^3 as a minimum
g = gravitational acceleration (m/s2)

Source: DN1/2012

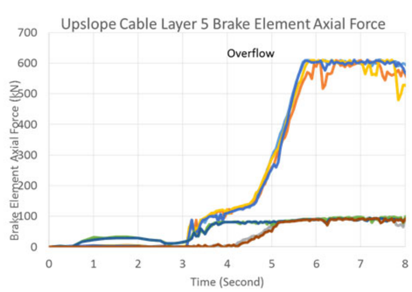
ARUP

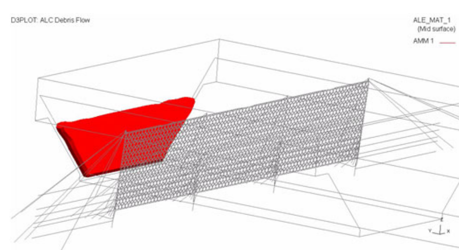
Simulation Results

Sensitivity Check

Increasing volume of 230 m^3 to overflow, and increasing impacting velocity to 15 m/s

- Brake element forces at horizontal cables are well within capacity, even for overflow @ 15m/s case, maximum utilisation is only **71%** at layer 7 (uppermost layer)





ARUP

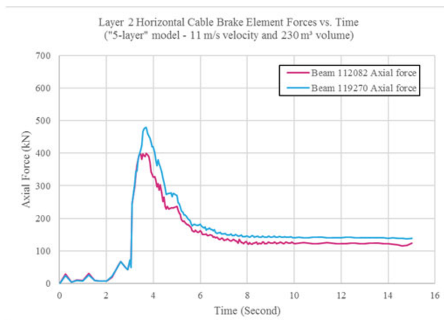
Simulation Results

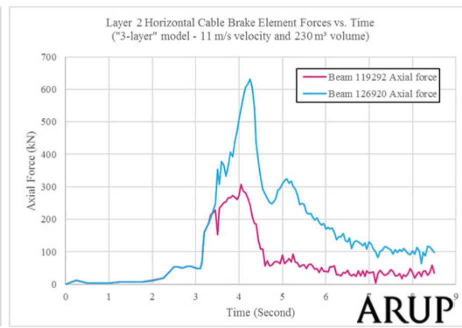
Parametric Study

Reducing the no. of horizontal cables

- Gradually reducing number of layers of horizontal cables from 7 > 5 > 3 > 2
- Other configuration, including number of cables per layer remain the same

- All configuration can sustain 230 m³ debris @ 11m/s, except for “2 layers model”, for which the deformation exceeds the acceptance criteria





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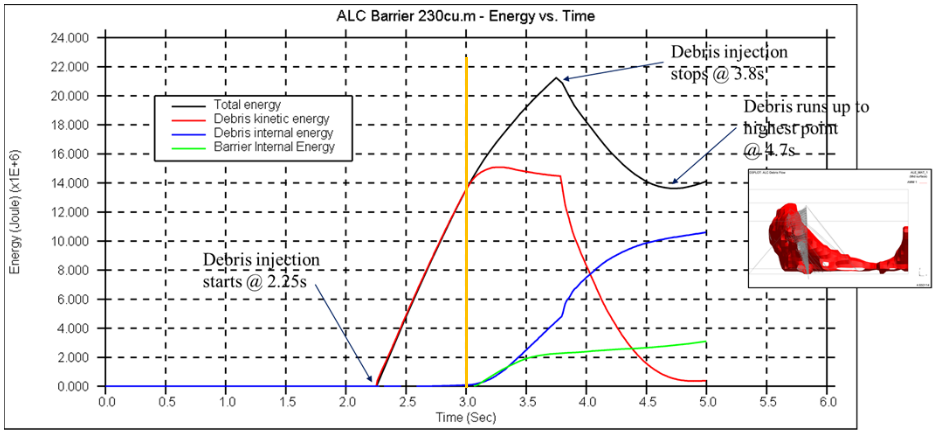
Discussion – Conservativeness of the Design

- Our Study shows there is high potential to use fewer layers of cables to sustain the same design debris flow event

- Debris-barrier interaction allows:
  - Slowing down of debris in subsequent surges
  - Additional energy could be dissipated within the retained debris mass e.g. internal turbulence
  - Reduce artificial conservativeness due to assumed impact pattern

Energy balance in LS-DYNA model



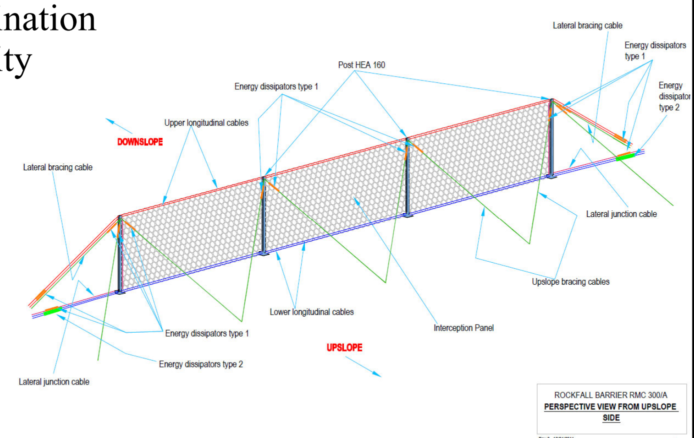
Barrier absorbed energy (BE) = 3,000 kJ
Debris Kinetic Energy at impact (KE) = 14,000 kJ
BE to KE Ratio = 20% only!

ARUP

More Study on Energy Balance of Barrier

- Similar debris flow interaction simulation on commercially available rock fall barrier
- 3,000 kJ Macaferri rock fall barrier

- Parameters to vary:
  - Channel inclination
  - Debris velocity



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More Study on Energy Balance of Barrier

Base Case

Base Case

Model ID	Slope (°)	Initial Velocity (m/s)	Debris Volume (m³)	Debris Kinetic Energy at impact (KE) (kJ)	Max. Barrier Total Energy (BE) (kJ)	BE to KE Ratio (%)
F (Base case)	0	5.0	100	1060	120	11

ARUP

More Study on Energy Balance of Barrier

Phase 1

Phase 1 – Increasing Velocity

Model ID	Slope (°)	Initial Velocity (m/s)	Debris Volume (m³)	Debris Kinetic Energy at impact (KE) (kJ)	Max. Barrier Total Energy (BE) (kJ)	BE to KE Ratio (%)
F (base case)	0	5.0	100	1060	120	11
N	0	7.5	100	2700	460	17
O	0	10.0	100	4900	1080	22

ARUP

More Study on Energy Balance of Barrier

Phase 2

Phase 2 – Increasing Slope Inclination

Model ID	Slope (°)	Velocity before impact (m/s)	Debris Volume (m³)	Debris Kinetic Energy at impact (KE) (kJ)	Max. Barrier Total Energy (BE) (kJ)	BE to KE Ratio (%)
N	0	9.0	100	2700	460	**17**
Q	10	10.0	100	3900	1140	**29**
K	15	9.1	100	2850	1030	**36**
R	30	10.1	108	2450	2040	**83**

Conclusions

Benefits of LS-DYNA in landslide modelling

- A thorough **3D back-analysis of landslides** can help to determine the probably causes of failure and recommend the necessary follow-up actions.
- LS-DYNA can be a useful tool for **detailed forensic investigations**, such as the analysis of the likely mode and sequence of failure and diagnosis of the causes of the landslide.
- In the event of landslide incident where the landslide debris hit an existing flexible barrier, **debris-flexible barrier interaction** can be modelled using LS-DYNA accurately.
- The coupled analysis enables detailed investigation of the **structural forces and energy balance** involved in the impact process.

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Remarks

- Dynamic analysis is required for dynamic problem.
- Pseudo-static approach or over-simplification of the model can render in overconservative design.
- With accurate typographical information, advanced computational model predicts the path of debris flow (trajectory) and time of arrival. The designer can position and test the mitigation works at the strategic (most effective) locations.

ARUP

Thank you

HKIE TRANSACTIONS, 2018
https://doi.org/10.1080/1023697X.2018.1462106

Check for updates

Advanced numerical analysis of landslide debris mobility and barrier interaction

Arthur K C Cheung[a], Jack Yiu[a], Harris W K Lam[b] and Eric H Y Sze[b]

[a]Ove Arup & Partners Hong Kong Limited, Hong Kong, PR China; [b]Geotechnical Engineering Office, Civil Engineering and Development Department, The Government of Hong Kong Special Administrative Region, Hong Kong, PR China

ABSTRACT
Mitigation of natural terrain hazards through the use of flexible and rigid barriers has become a common type of geotechnical work in Hong Kong. The current design approach for these structural countermeasures typically involves separate debris mobility modelling and structural analyses of barriers subject to pseudo-static impact loadings. This practical approach, however, could not realistically account for the dynamic debris–barrier interaction. With a view to better capturing the response of barriers under debris impact, effort has recently been devoted to developing an advanced numerical technique to model debris flows, barrier structural responses and the impact dynamics in a coupled manner. This paper presents some recent advances made in establishing the numerical technique of coupled analysis using a three-dimensional finite-element computer code LS-DYNA. The methodologies of modelling the landslide debris mobility, the large-deformation non-linear behaviour of a flexible barrier under impact and the coupled analysis of debris–barrier interaction are introduced. Back analyses of selected landslide events and debris impact tests of flexible barriers for verification of the computer models are discussed. The coupled analysis enables detailed investigation of the energy balance involved in the impact process. Preliminary results of this energy analysis are also presented.

ARTICLE HISTORY
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Accepted 3 April 2018

KEYWORDS
Debris mobility; flexible barriers; debris–barrier interaction; energy balance; LS-DYNA; finite-element modelling

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ARUP

HK工E THE HONG KONG INSTITUTION OF ENGINEERS 香港工程師學會
Geotechnical Division 岩土分部

HKIE Workshop on
Numerical Modelling for Design of Flexible Debris-resisting Barriers

Organized by

Geotechnical Division, Hong Kong Institution of Engineers

Working Group on Application of Innovative Technology in Geotechnical Engineering

Supporting organization

Department of Civil & Environmental Engineering, Hong Kong Polytechnic University

Prof. SL Chan, Dr. ZH Zhou, Dr. YP Liu
Mr. JW He and Dr. L Zhao

16th April, 2019
The Hong Kong Polytechnic University

THE HONG KONG POLYTECHNIC UNIVERSITY 香港理工大學

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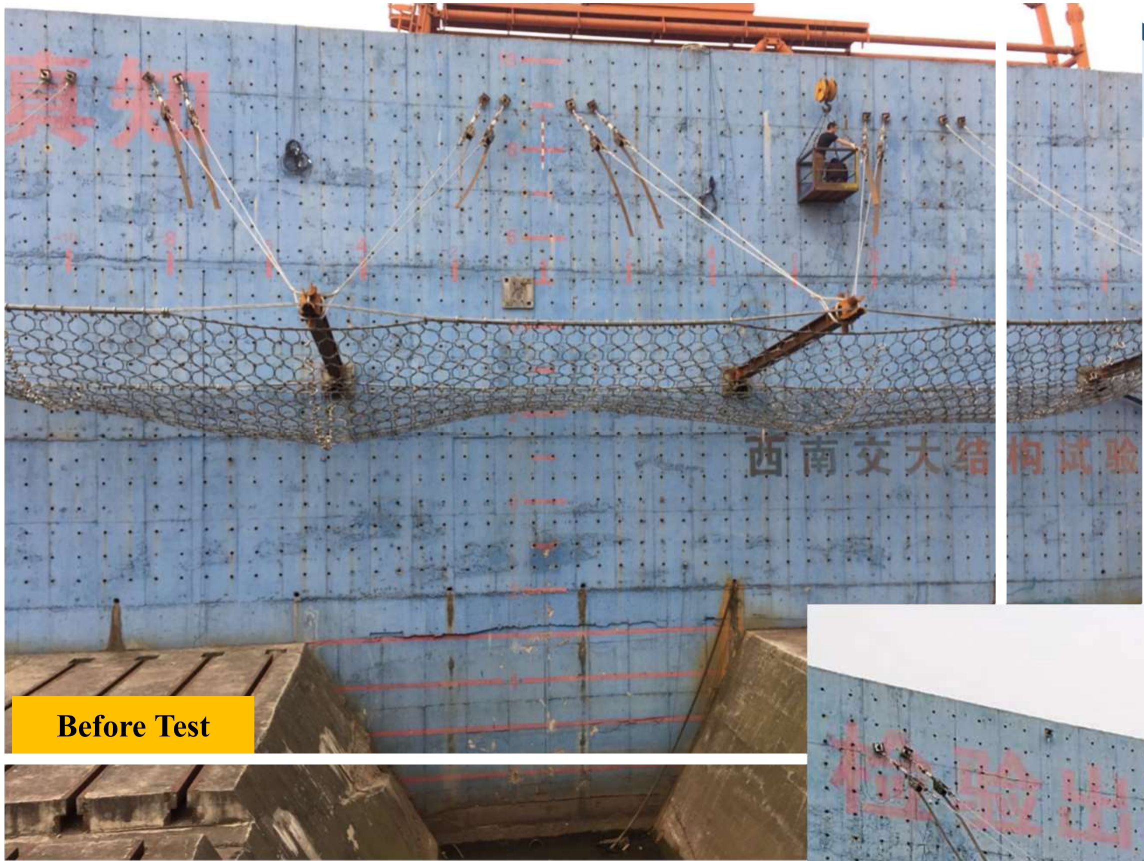


Before Test

After Test

Content

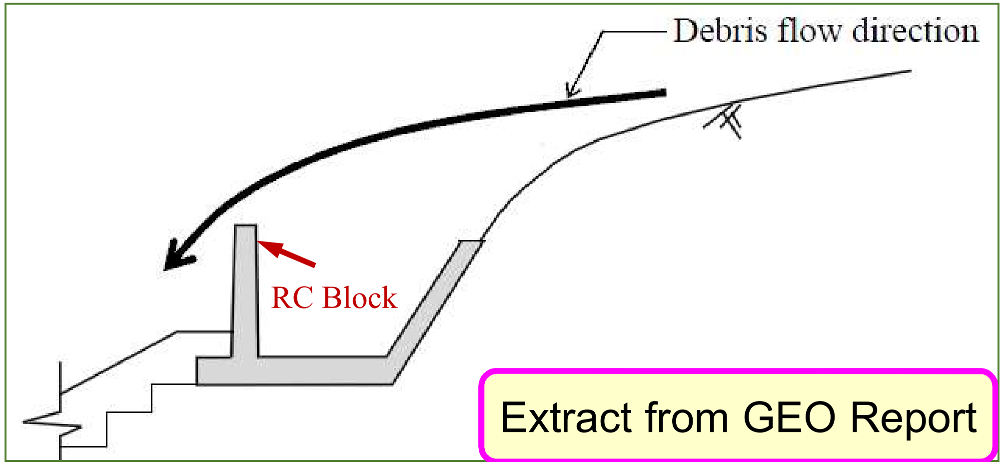
What's flexible barrier? *- Protection system against landslide*

What's flexible barrier? *- Protection system against rockfall*

Why flexible barrier?

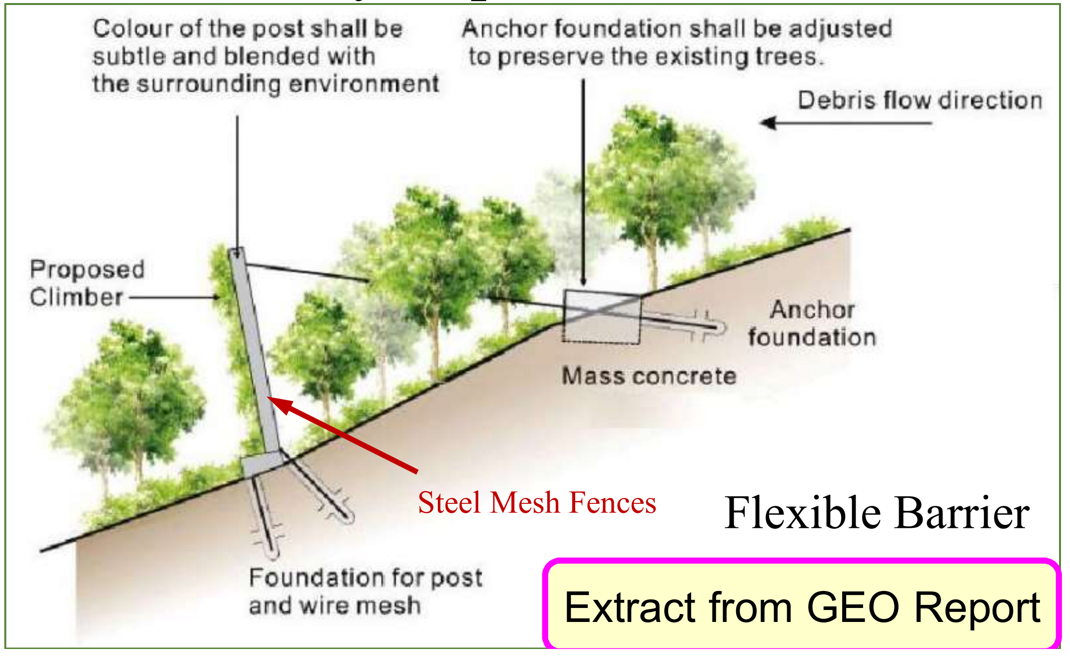
- Old Solution: Rigid Barrier
  - Difficulty in Construction;
  - Higher Impact Load;
  - Higher Cost;
  - Environmental Impact;
  - Opaque & Less Aesthetics;

…



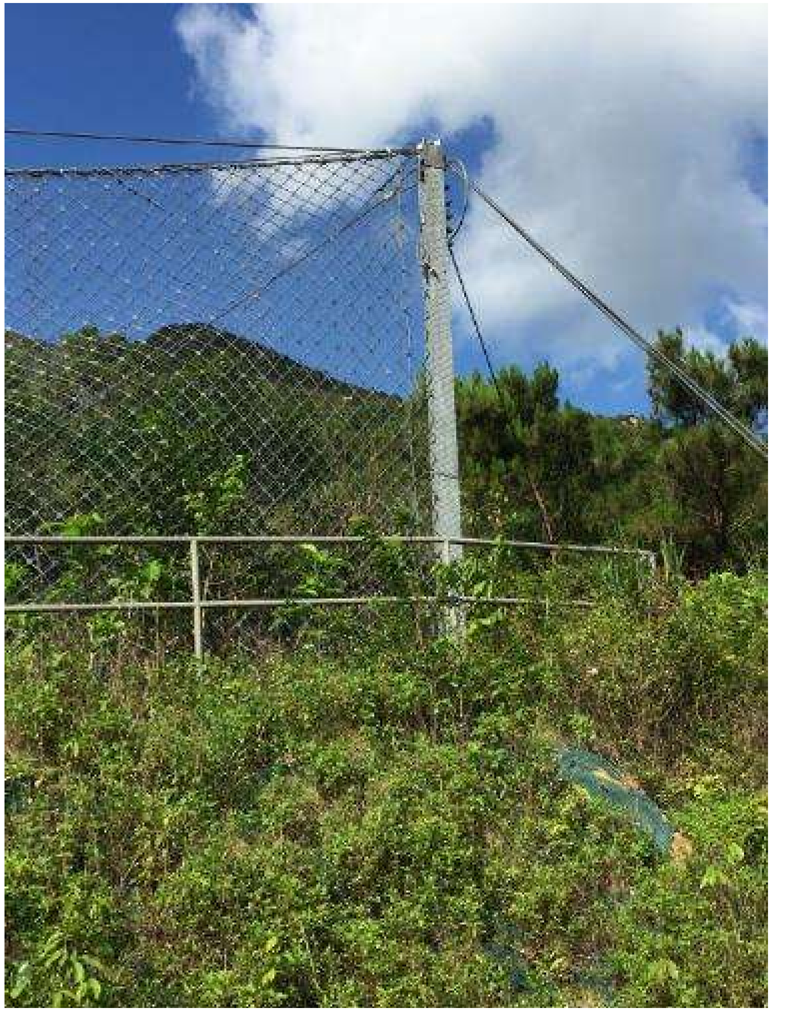
Why flexible barrier?

- New Solution: Flexible Barrier
  - Easy & Fast Construction;
  - Lower Impact Load; 以柔克刚
  - Lower Cost;
  - Less Environmental Impact;
  - Transparent & Good Aesthetics;
  - Easy Repair…



Flexible Barrier

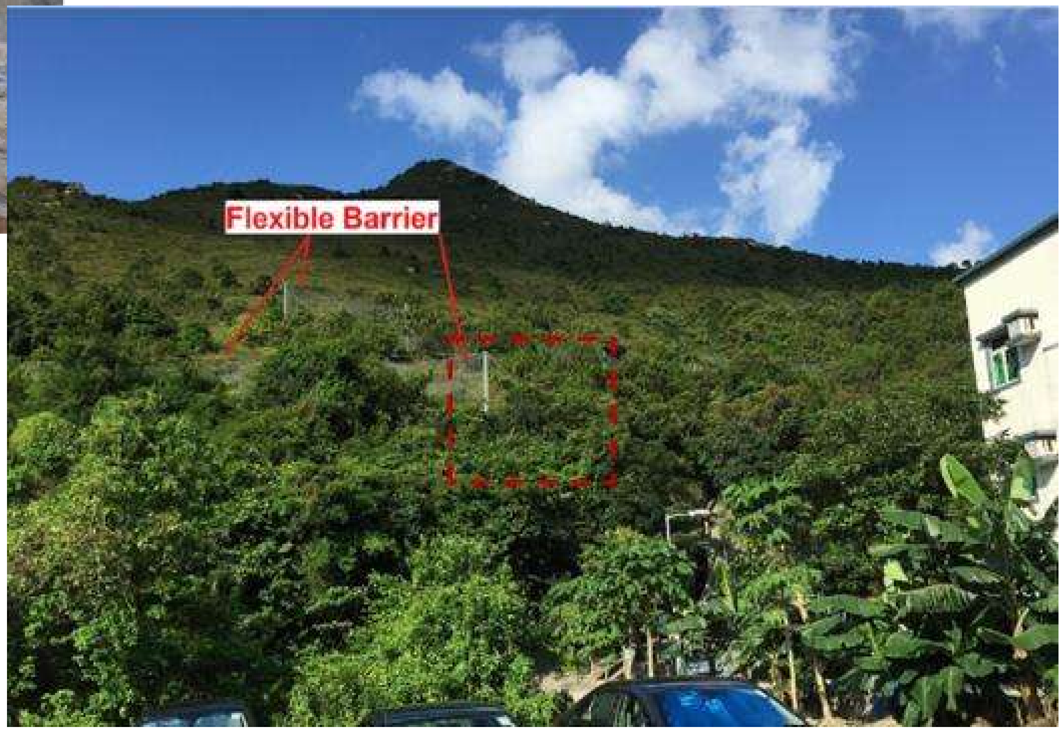
Extract from GEO Report



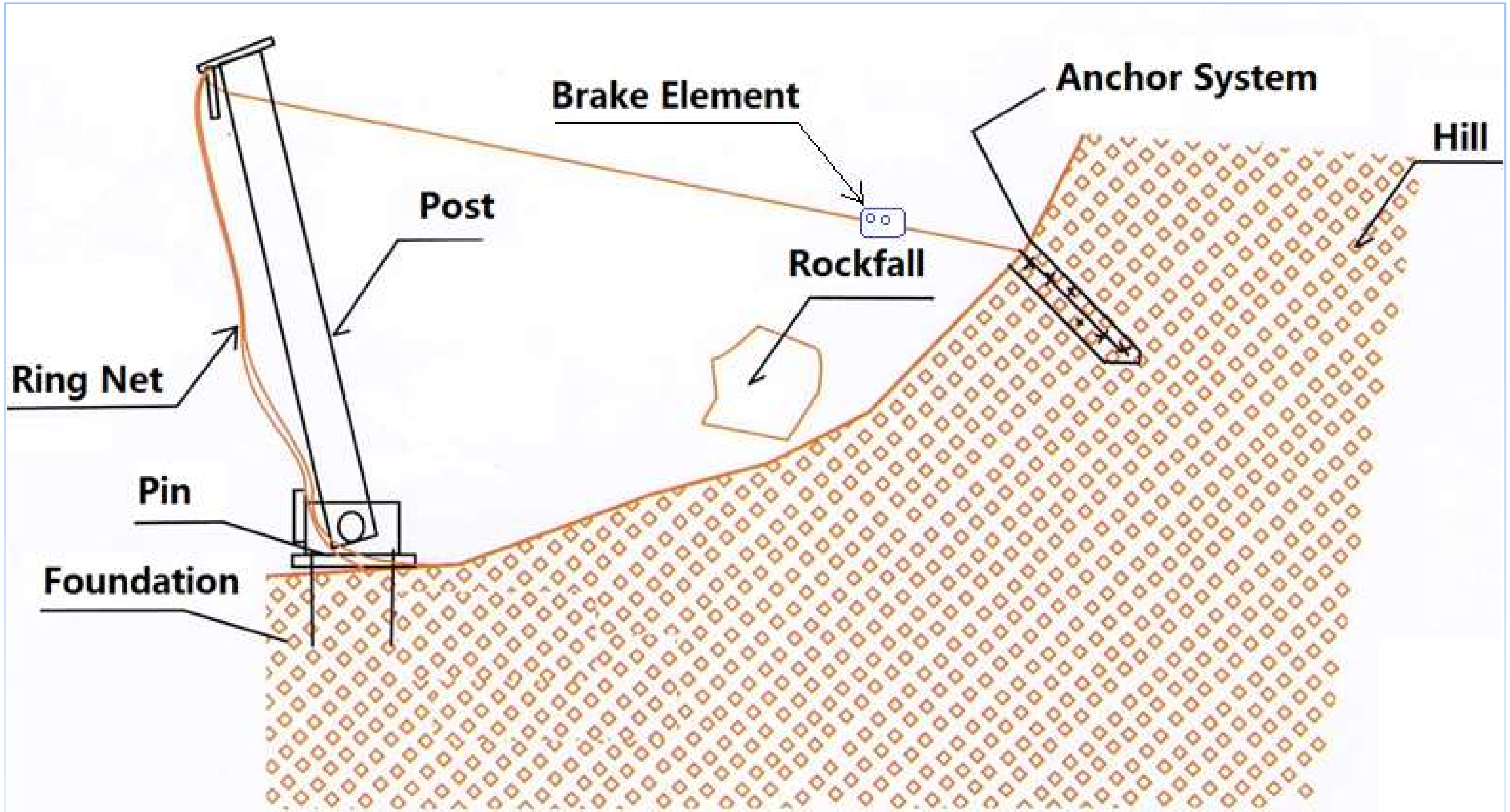
Why flexible barrier?

Protection Barrier

Rigid vs. Flexible



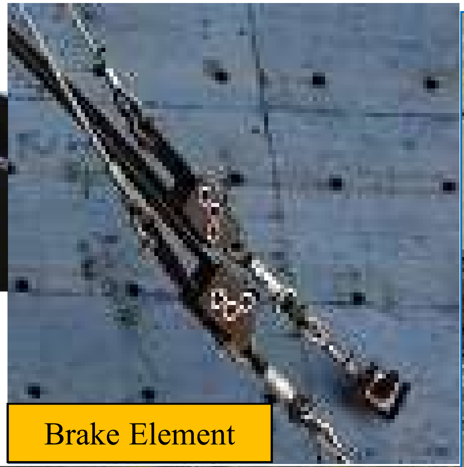
What's flexible barrier?



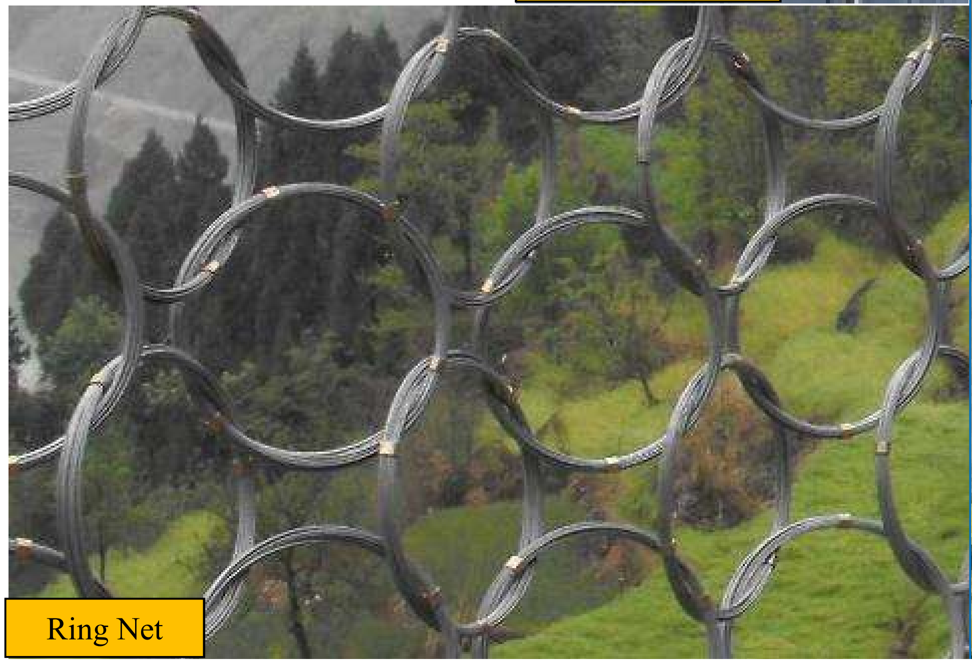
Section view of a typical flexible barrier system

What's flexible barrier?

Shackle



Brake Element



Ring Net

Flexible Barrier System

Why conduct this research in Hong Kong?

- Rocks falling from slopes can be very dangerous to buildings, vehicles in highways and pedestrians along hill side. Normally engineers build rigid or flexible barriers to capture these rocks against their collision with other buildings, vehicles or humans.

- Foreign proprietary products used in Hong Kong (**High cost, Black box, Unsafe, Standard product but not tailor-made**, …)

- This project is aimed to develop new a energy absorbing device (EAD), which is one of the major component of flexible barrier system. → *Absorb >70% Impact Energy*

Why conduct this research in Hong Kong?

- Energy absorbing device – *Brake Element*

– Major component of the flexible barrier system;

– High energy absorbing capacity;

– Made of metal and mounted on steel cables;

Why conduct this research in Hong Kong?

- Energy absorbing device – patented and expensive, limit the application of flexible barrier system in Hong Kong.

Proprietary products in market:

- Geobrugg
- Maccaferri
- Trumer
- Isotop
- Tubosider
- EI Montagne

Content

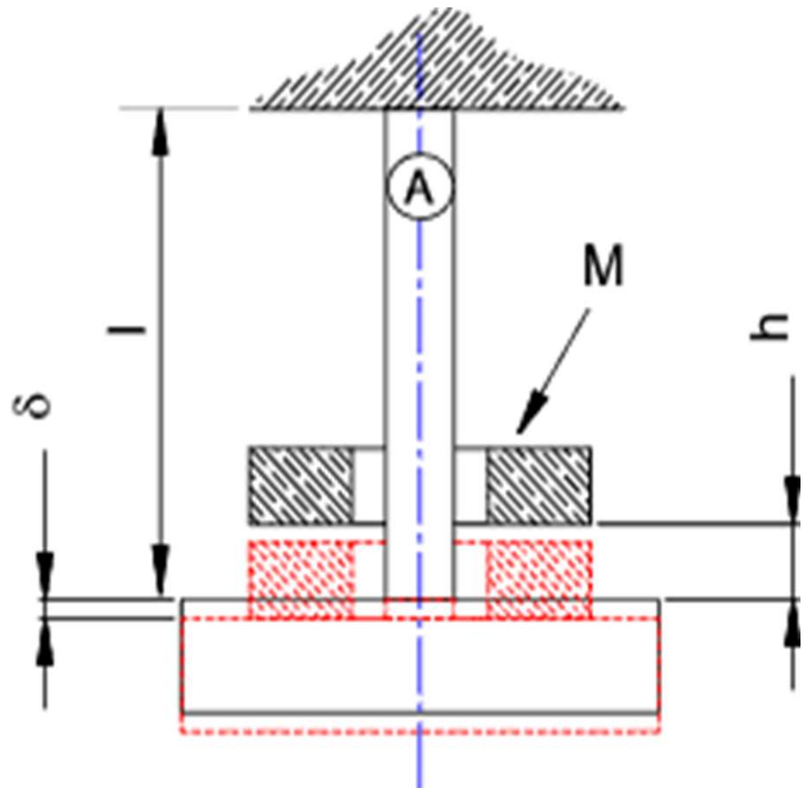
Linear Impact deflections and stresses under gravitational loads

- Consider a loading shown below with a ring Mass M(kg) of weight W= M.g (N) dropped through a distance "h" onto a vertical bar with stiffness as a spring with a stiffness of k (N/m).

- The support bar has a length l (m),

  Area A (m^2)

  Modulus of elasticity E (N/m^2)



$$W(h + \delta_{max}) = \frac{1}{2}(k\delta_{max})\delta_{max}$$

$$\delta_{max}^2 - \frac{2\mathrm{W}}{k}\delta_{max} - 2\left(\frac{W}{k}\right)h = 0$$

$$\delta_{max} = \frac{W}{k}\sqrt{\left(\frac{W}{k}\right)^2 + 2\left(\frac{W}{k}\right)h}$$

$$\delta_{st} = \frac{W}{k} = \frac{\mathrm{WI}}{AE}$$

$$\boldsymbol{\delta_{max} = \delta_{st} + \sqrt{(\delta_{st})^2 + 2\delta_{st}h}}$$

$$\boldsymbol{\delta_{max} = \delta_{st}\left(1 + \sqrt{\left(1 + \frac{2h}{\delta_{st}}\right)}\right)}$$

The resultant maximum force is

$$P_{max} = k\,\delta_{max}$$

and the resultant maximum stress is

$$\sigma_{max} = P_{max}/A$$

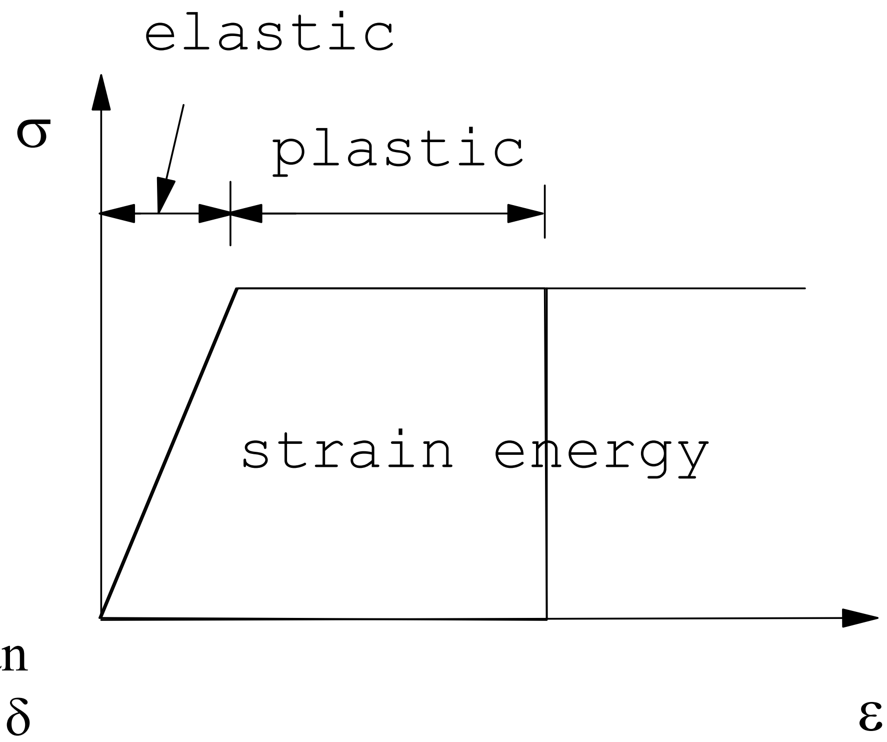
$$\sigma_{max} = \sigma_{st}\left(1 + \sqrt{\left(1 + \frac{2h}{\delta_{st}}\right)}\right)$$

For the calculation of the stress due to a sudden load, h = 0

$$\sigma_{max} = 2\sigma_{st}$$

- As can be seen in the above simple equations , the weight impact onto the support to make it deform until all of the potential energy has been absorbed, either in elastic or plastic range.
- The equations above compute the initial maximum deformation for the most highly stressed condition.

$$mgh = \frac{1}{2}mv^2 = \int \sigma\varepsilon \, dV$$



$$A = \pi r^2 \qquad F = \frac{mgh}{\delta}$$

So, we have less force for larger displacement and a flexible barrier produce less reactions on supports or foundation than a rigid barrier which has smaller deflection δ

A key feature of flexible barrier system is that it is light yet they can absorb high impact energy through the large elasto-plastic deformations and sliding node action.

This is achieved by sliding motion of nodes or element connection, the displacement of the cable net and the activation of energy dissipating devices mounted on the connecting cables.

Flexible Barrier Analysis

- Energy absorbing mechanism:

  Plastic + large elastic deformation
- Three-dimensional nonlinear analysis

  → *Geometrical and material nonlinearity*
- Large deflection analysis + Contact analysis
- Debris flows load → *Force vs. Energy design*
- Brake element model → *from Test*
- Sliding ring element → *Ring net*
- Sliding cable element → *Steel rope*

FORCE DESIGN OF ROCKFALL BARRIER

- The external forces, sum of previous static forces on net + dynamic forces on net multiplied by an amplification factor, will be applied onto the net and check for any breakage in the element as indicated by elongation greater than the maximum elongation of every element. Automatically plastic strain is allowed.

ENERGY DESIGN OF ROCKFALL BARRIER

- For a typical barrier system, the kinetic energy E of debris flows or falling rock and the total strain energy U of the barrier system can be given as below:

  $E = (1/2)\, mv^2$ - Kinetic energy

  $U = U_b + U_c + U_r$ - Total strain energy

  in which, m is mass of debris flows or falling rock; v is initial velocity of debris flows or falling rock; U_b, U_c and U_r are strain energy of brake elements, cables and net ring, respectively.

- The design criteria of barriers safely undergoing specified dynamic load may be described as:

  $U \geq E$

Energy vs. Force Methods

Energy Method

(To determine E first) → →

Impact energy *Structure* *Load of force*

← ← (To determine force first)

Force Method

Energy vs. Force Methods

- Energy is a simple and convenient indicator, but not all components reach their maximum energy absorption capacities simultaneously.

  → *Cannot simply sum up energy capacities of all components as system capacity*

- Force method is more direct and able to cater for uneven force distribution.

  → *The magnitude of force is unknown.*

  (Ft = mv, t is unknown, so F is unknown)

Assume load pattern →

Increase loads to achieve design energy

$U \geq E$

Content

Nida-MNN – A product of Nida family (*BD Reference: S0884*)

- NIDA-MNN is specially developed for nonlinear analysis of cable structures with Moving Node Net, such as rockfall barriers, debris flow barriers.
- NIDA-MNN provides an unified and user-friendly interface to assist the engineers to design a flexible barrier system like conventional steel structures.
- Unlike the commercial FE software using solid element to simulate flexible barrier, NIDA-MNN uses advanced beam-column element which leads to significant saving of modelling and computational time.

Nida-MNN – A product of Nida family (*BD Reference: S0884*)

BD Approval Letter of Nida-MNN

BUILDINGS DEPARTMENT

YOUR REF 來函檔號 :
OUR REF 本署檔號 : 56 in BD GR/OA/71 STR(203)
FAX 圖文傳真 : 2626 1762
TEL 電話 : 3152 3021
www.bd.gov.hk

30 November 2016

Mr. Lau Chi Kin
c/o Sun Hung Kai Architects and Engineers Ltd.
22/F, Sun Hung Kai Centre,
30 Harbour Road,
Hong Kong

Dear Sir,

Application for Renewal of Prior Acceptance of Computer Program
NIDA-MNN (Version 2013)
(Large Deflection Analysis of Cable Net)

I refer to your application and document dated 3 October 2016, 12 October 2016 and 25 October 2016 regarding the renewal of prior acceptance for the above computer program.

2. Based on your assessment of the computer program, I hereby grant my renewal of prior acceptance of its use in submissions made under the Buildings Ordinance for the validity period listed below and subject to the conditions stipulated in paragraphs 3 to 6.

Program Title	BD Reference Number	Valid Until
NIDA-MNN (Version 2013) (Large Deflection Analysis of Cable Net)	S0884	24 November 2019

BD Approval Letter of a Project Designed by Nida-MNN

BUILDINGS DEPARTMENT

17 MAY 2016

YOUR REF 來函檔號 :
OUR REF 本署檔號 : BD 3/9226/14
FAX 圖文傳真 : 2845 1559
TEL 電話 : 2626 1461
www.bd.gov.hk

11 May 2016

LAU Chi Kin
22nd Floor,
Sun Hung Kai Centre,
30 Harbour Road,
Wanchai, Hong Kong.

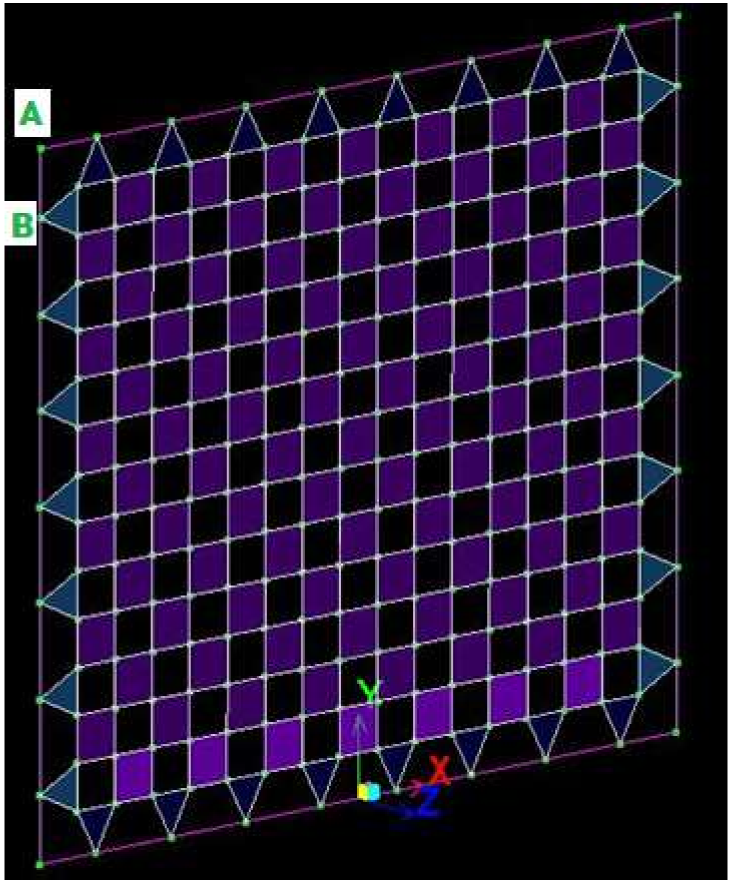
Dear Sir,

King Sau Lane, Area 4, Tuen Mun - TMTL
515 (formerly TM misc 271)

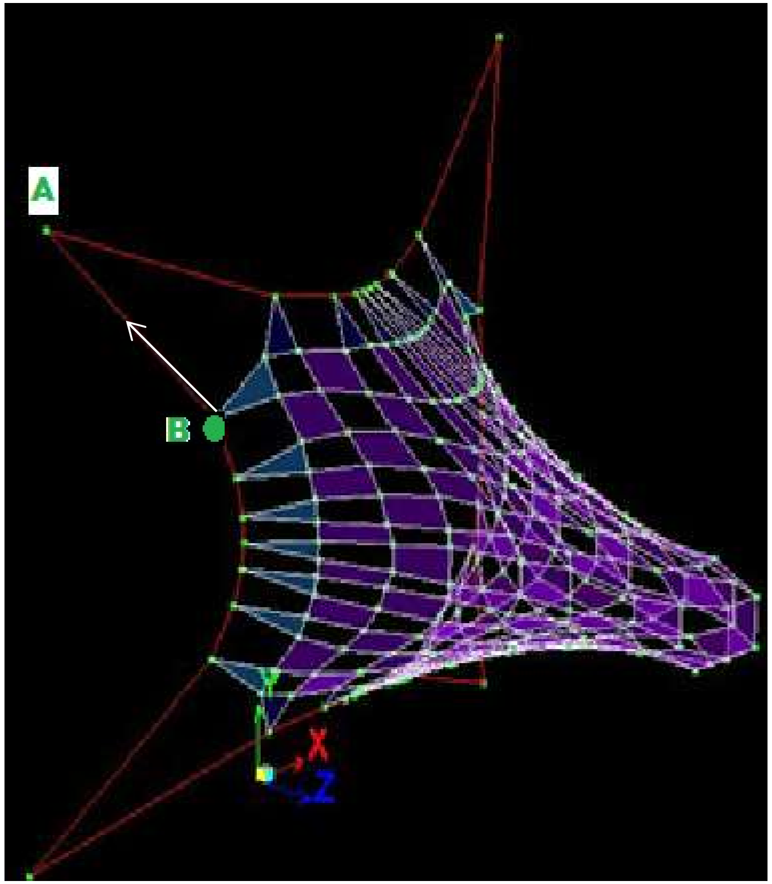
I refer to your application received on 3 March 2016 for approval of proposals in respect of Foundation (Mini-Piles), Foundation (Socketed Steel H-Piles), Pile Cap and Flexible Barrier.

2. Your submission of plans has been checked under the curtailed check system announced in Practice Note for Authorized Persons, Registered Structural Engineers and Registered Geotechnical Engineers ADM-19. On this basis, I am satisfied that your submission is fundamentally acceptable and may be approved.

Computer modeling
Moving node algorithm

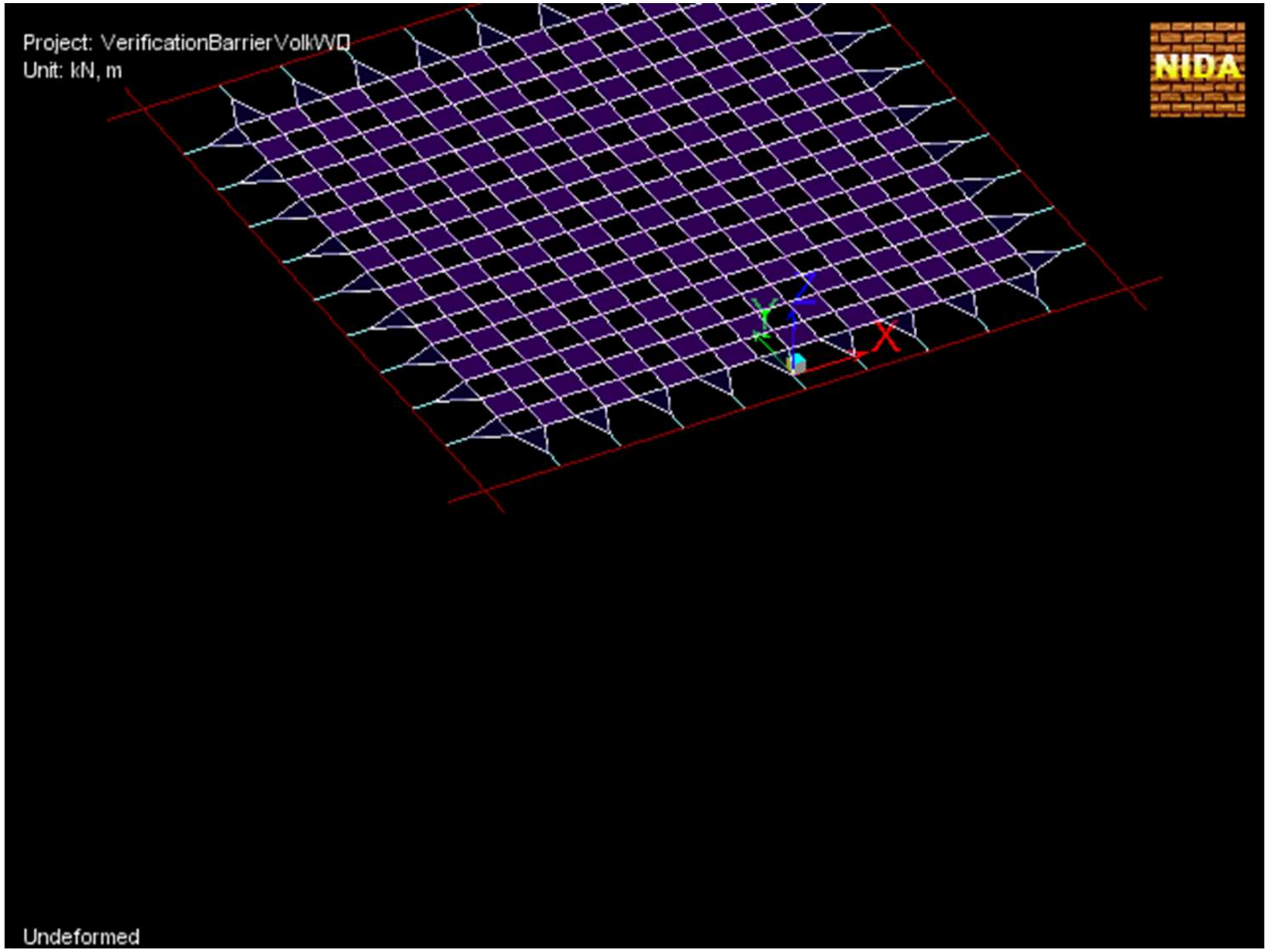


Before impact of rockfall



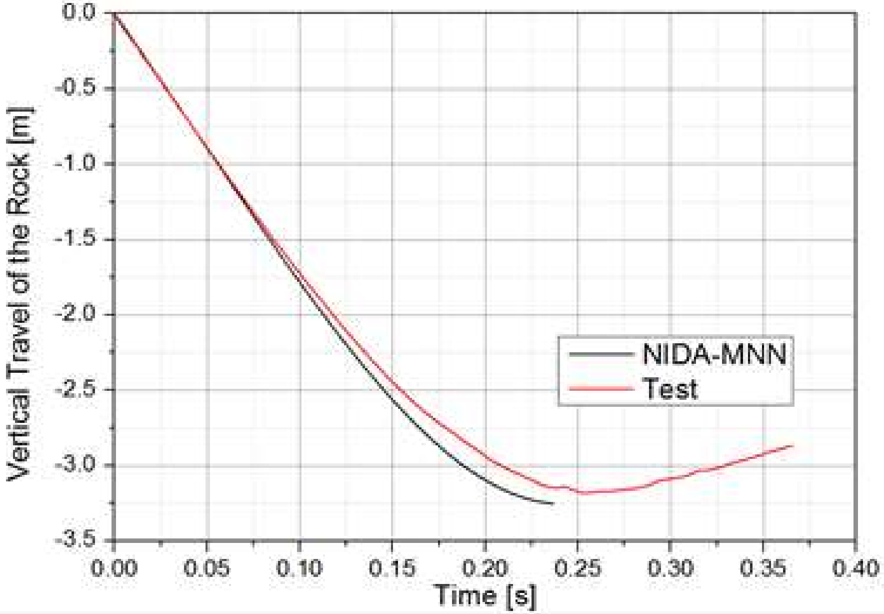
After impact of rockfall

Numerical Simulation: Rockfall



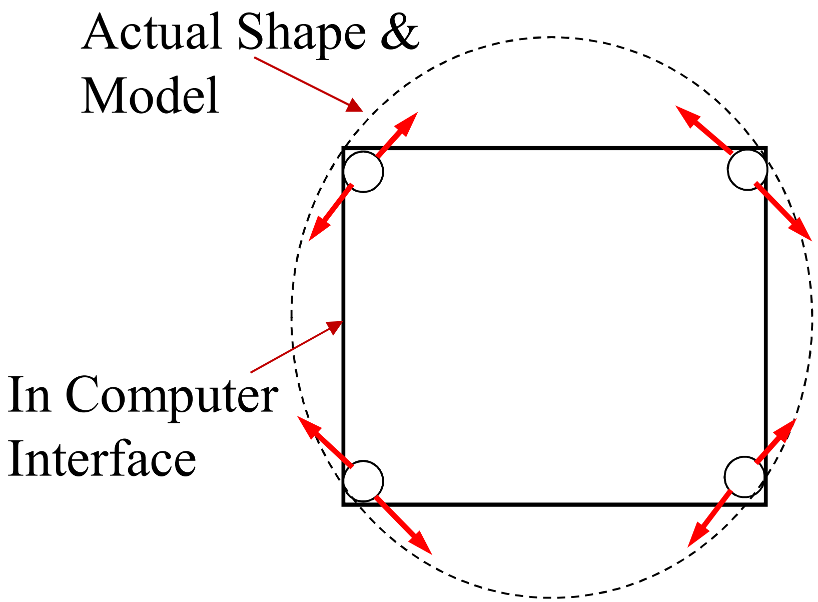
Test and Simulating Curve

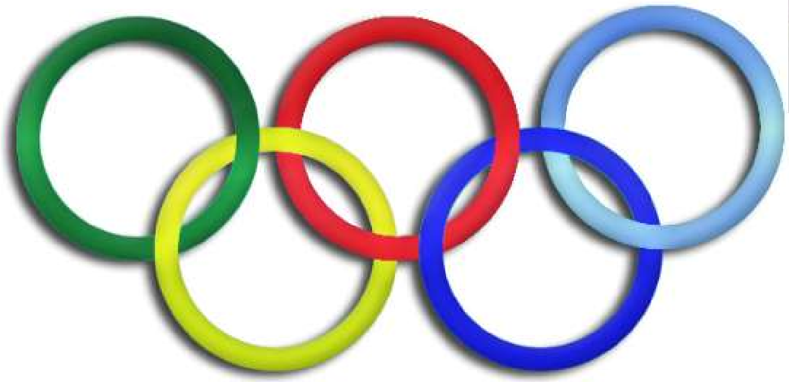
VolkWein



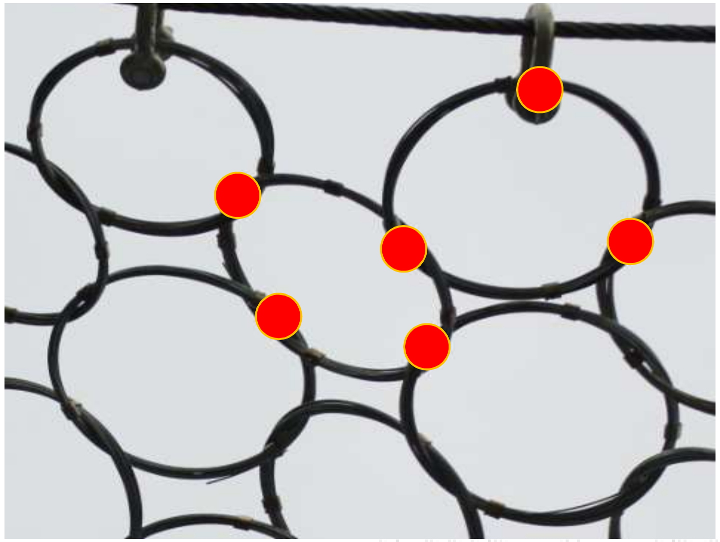
Modeling of Ring Net

- Each ring net connect at 3 to 4 points
- Connection point between every two ring nets is moveable
- Modeled by a new develop element considering contact behavior
- Friction force is considered

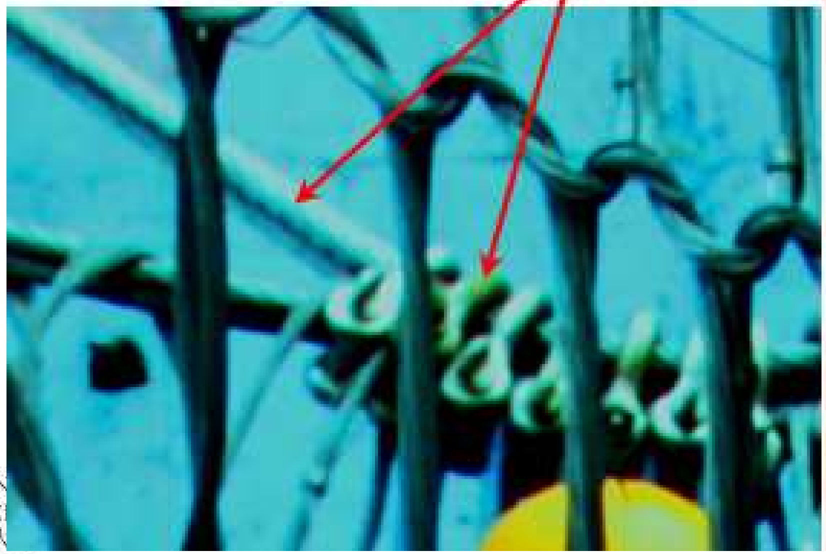




Before sliding

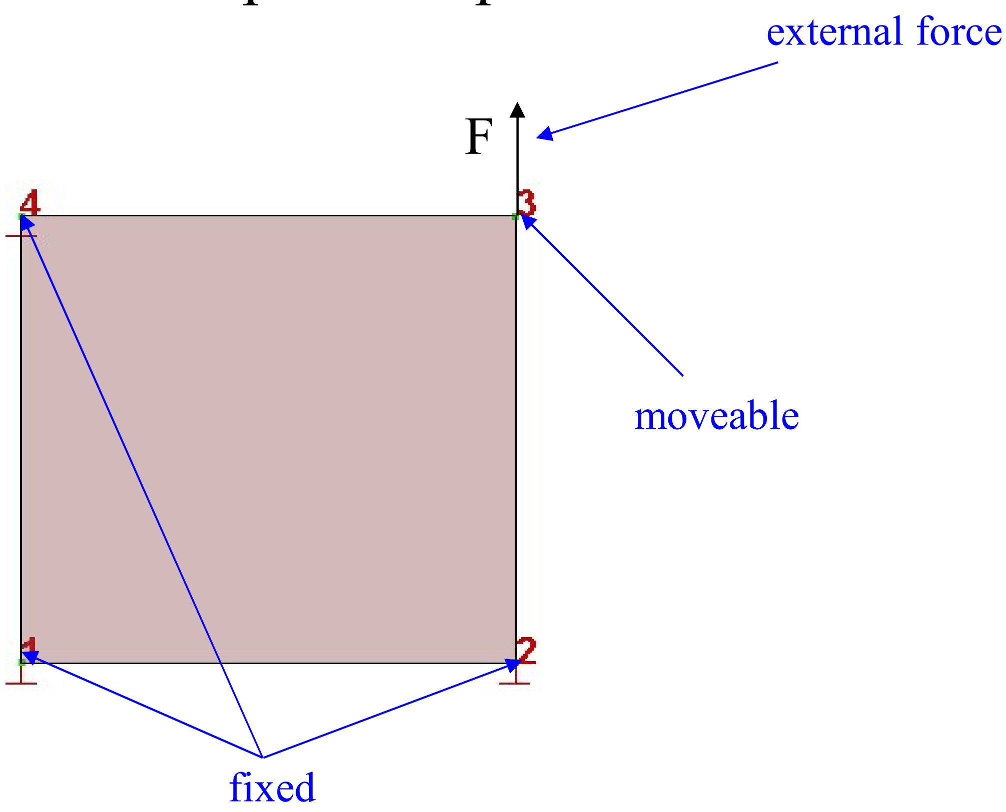


After sliding



Modeling of Ring Net

- Sliding ring element – a simple example

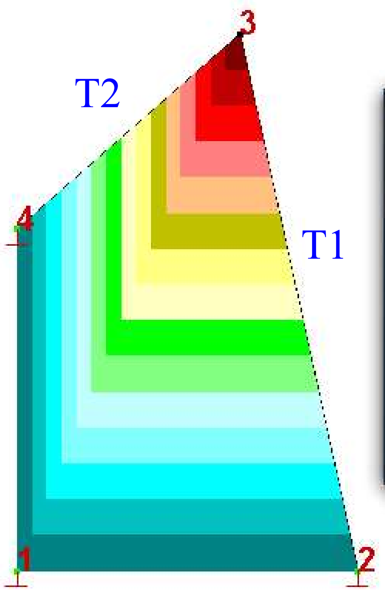


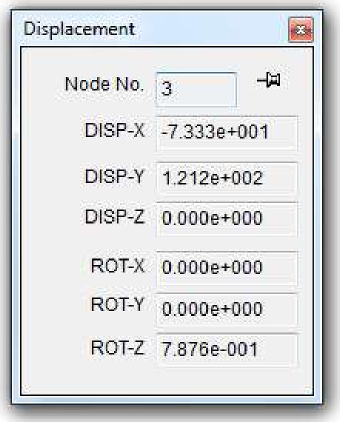
Simple example of sliding ring element

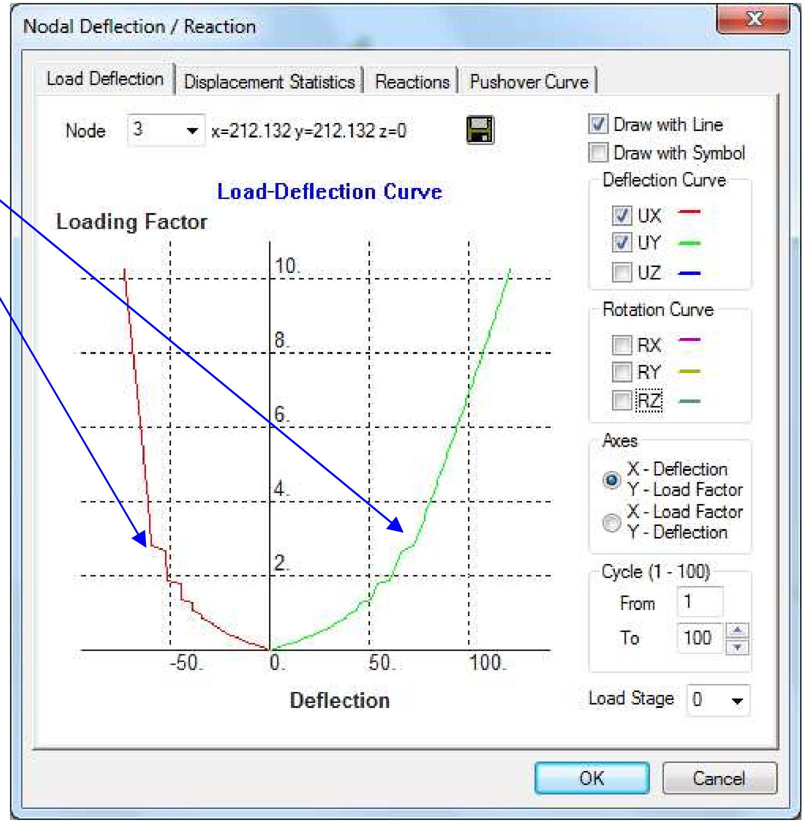
Modeling of Ring Net

Sliding

Jump due to friction







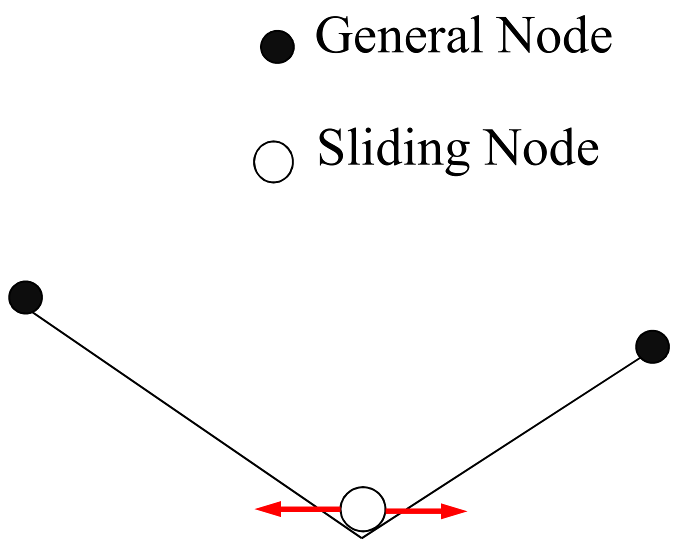
Tension force T1 = Tension force T2 + Frictional force

Deformed Shape of Ring Cable Element

Load-Deflection Curve

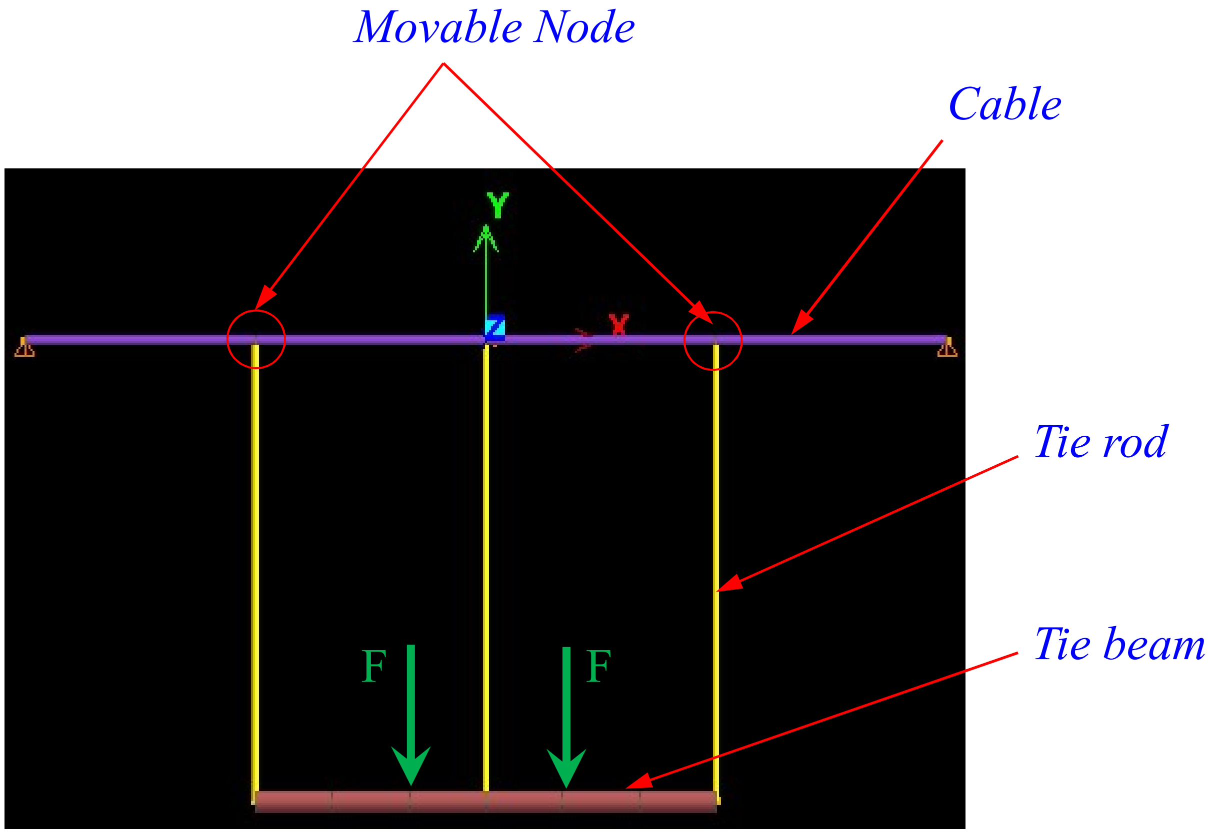
Modeling of Cable Rope

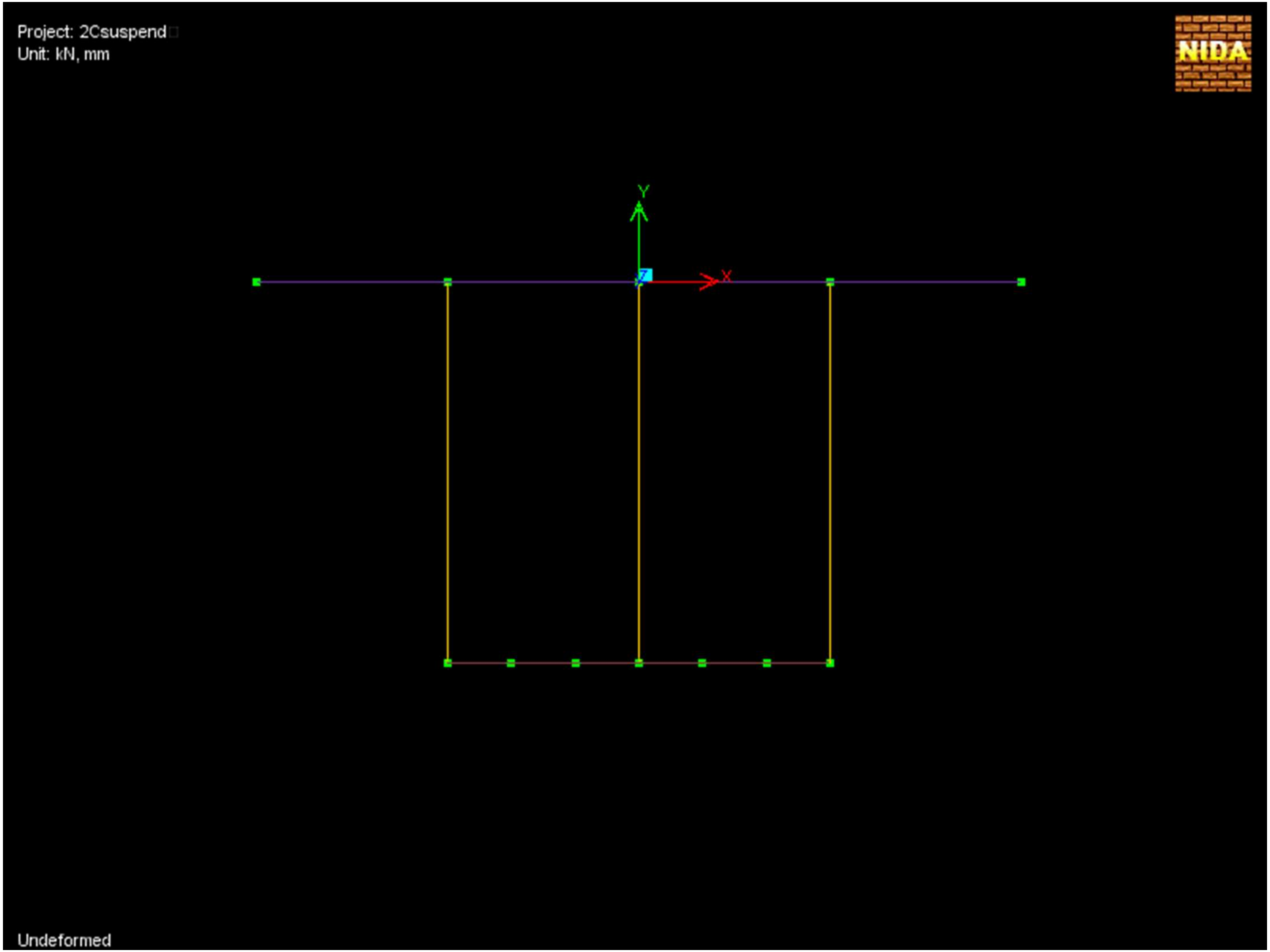
- Several segments allowed
- Connection point between rope and ring net is moveable
- Modeled by a new develop element considering contact behavior
- Friction force is considered
- Brake elements at any one or two segments



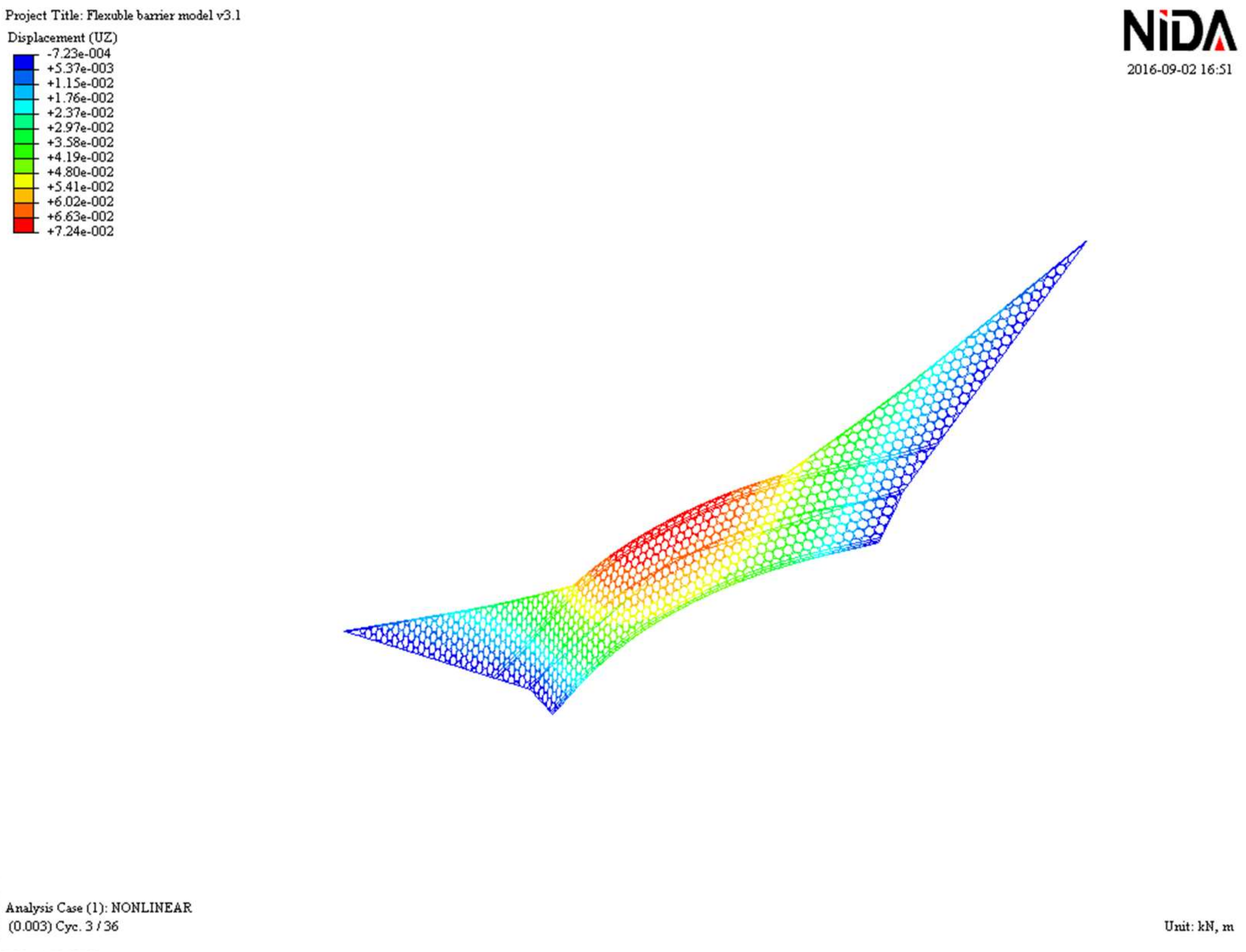
Modeling of Cable Rope

- Sliding cable element – a simple example




Project: 2Csuspend
Unit: kN, mm
NIDA
Y
X
Z
Undeformed

Numerical Simulation of Barrier under Debris Flow – Force Approach



Loading Assessment

Loading of Energy

For rock falling: $m v^2 / 2 = m g h$

For debris flow: $< m v^2 / 2$

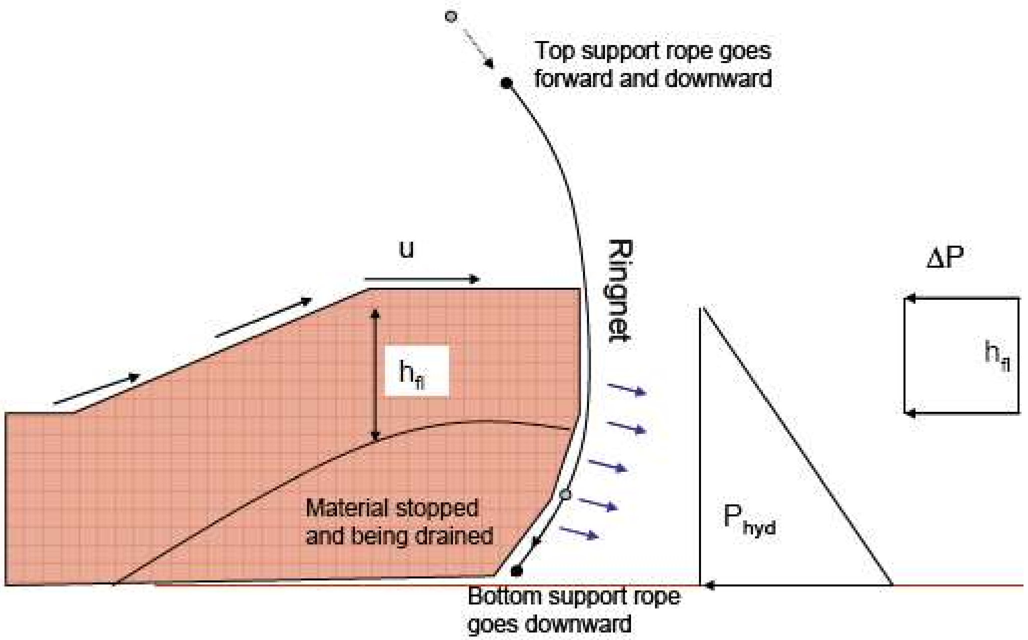
Loading of impact pressure

For rock falling: ???

For debris flow: $= \alpha \rho v^2$

Debris Flow – Force Approach

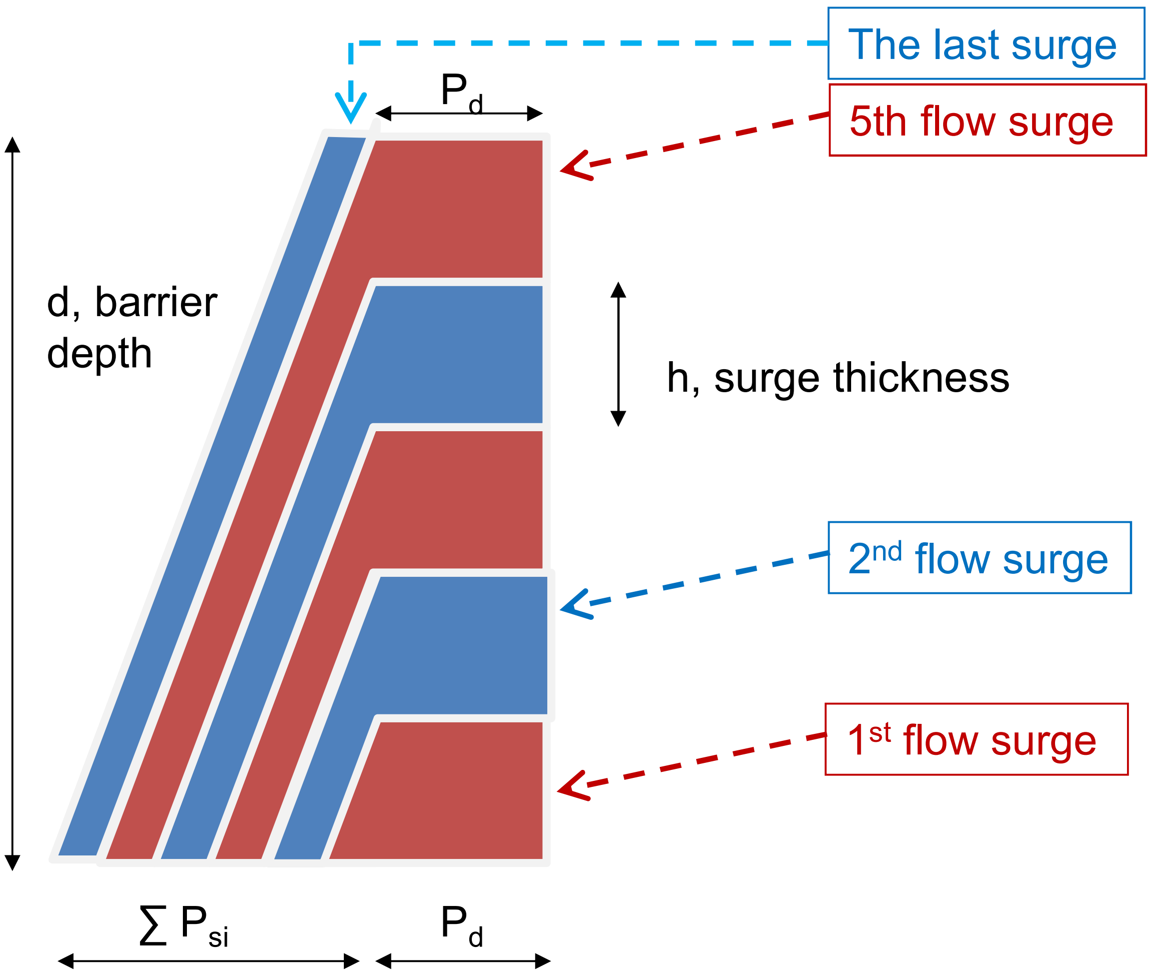
Dynamic pressure + hydrostatic pressure



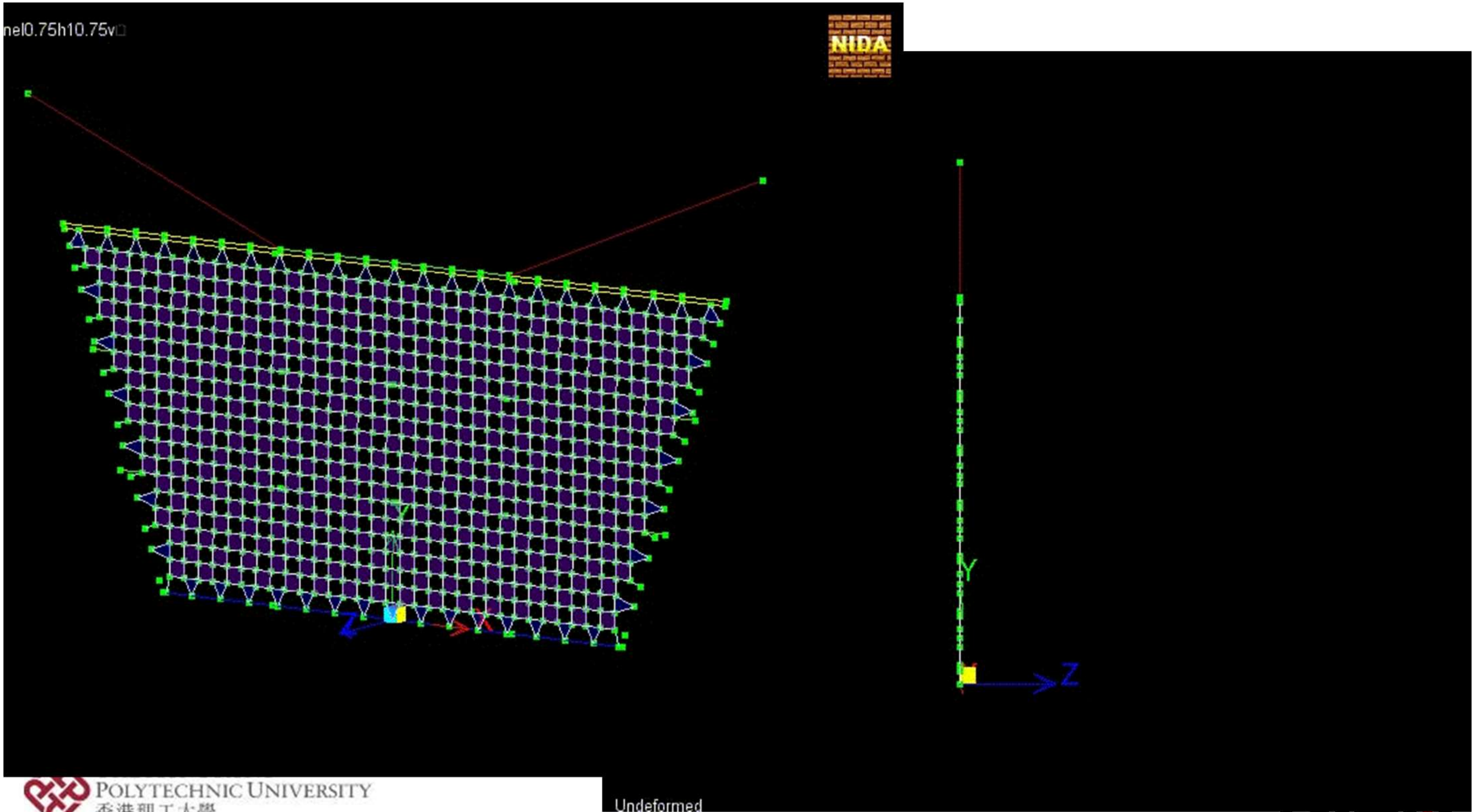
Extract from publication

Debris Flow – Force Approach

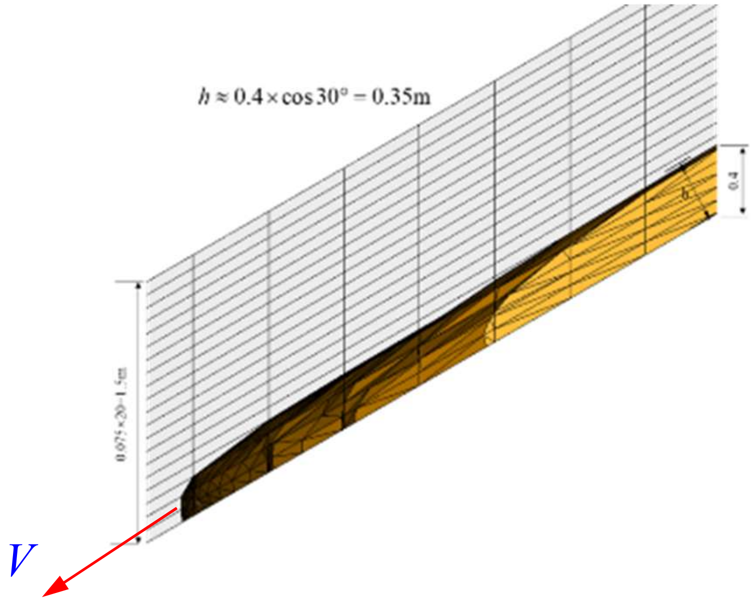
The ith debris flow pressure: $P_{si} = \rho\, g\, h$, $P_d = \alpha\, \rho\, v^2$ (kN/ m^2)

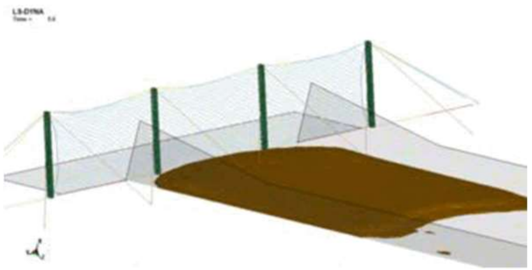


Debris Flow – Force Approach

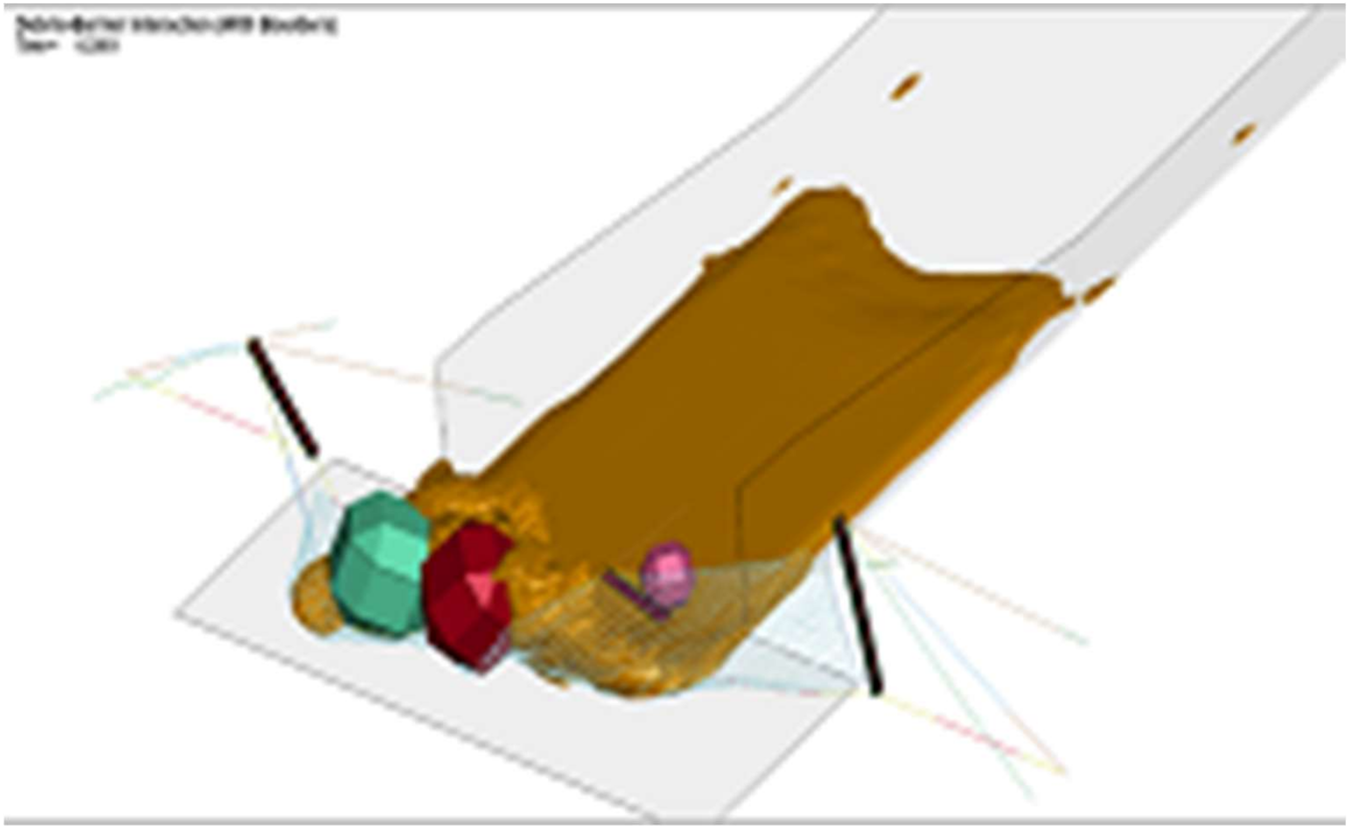


Mobility Analysis of Debris Flow



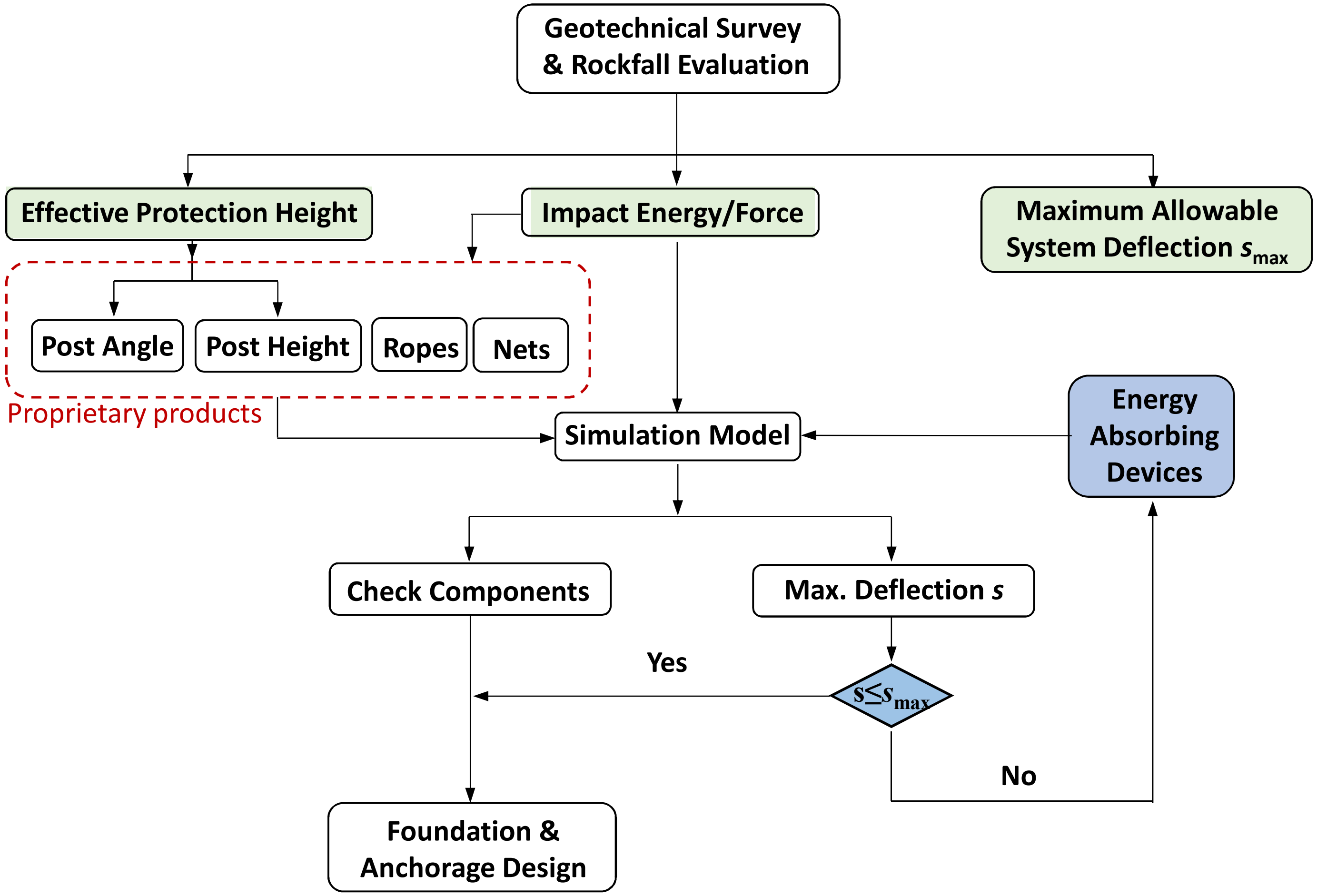


Interaction Analysis of Debris Flow + Boulder + Net



Ls-Dyna

Design Flowchart Using Nida-MNN



- Flexible barrier system is light yet they can absorb high energy through the large elasto-plastic deformations and sliding node action.
- NIDA-MNN is specially developed for flexible barrier system against rockfall and debris flow.
- NIDA-MNN is a robust and simple software for modelling of flexible barrier system against rockfall and debris flow.
- Flexible barrier system can be designed and fabricated in Hong Kong.

THANK YOU

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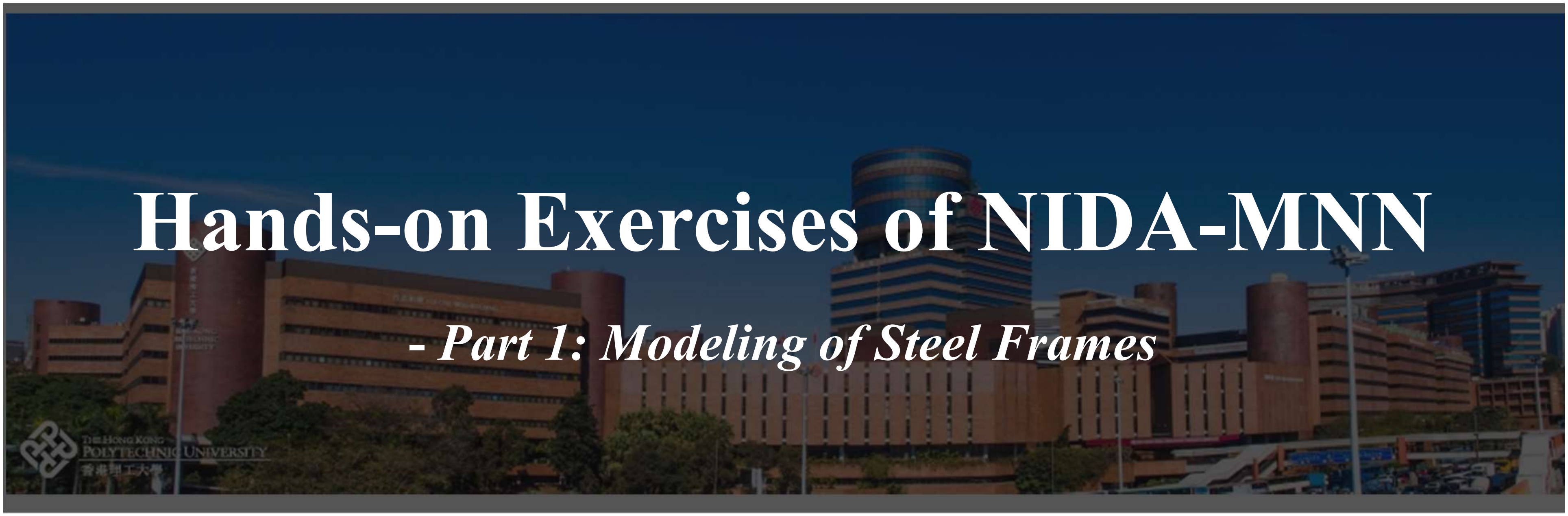
Workshop on Numerical Modelling for Design of Flexible Debris-resisting Barriers

Organized by

Geotechnical Division, Hong Kong Institution of Engineers

Supported by

Department of Civil and Environmental Engineering, The Hong Kong Polytechnic University



Hands-on Exercises of NIDA-MNN

- Part 1: Modeling of Steel Frames

Prof. SL Chan, Dr. ZH Zhou, Dr. YP Liu

Mr. JW He and Dr. L Zhao

16th April, 2019

The Hong Kong Polytechnic University

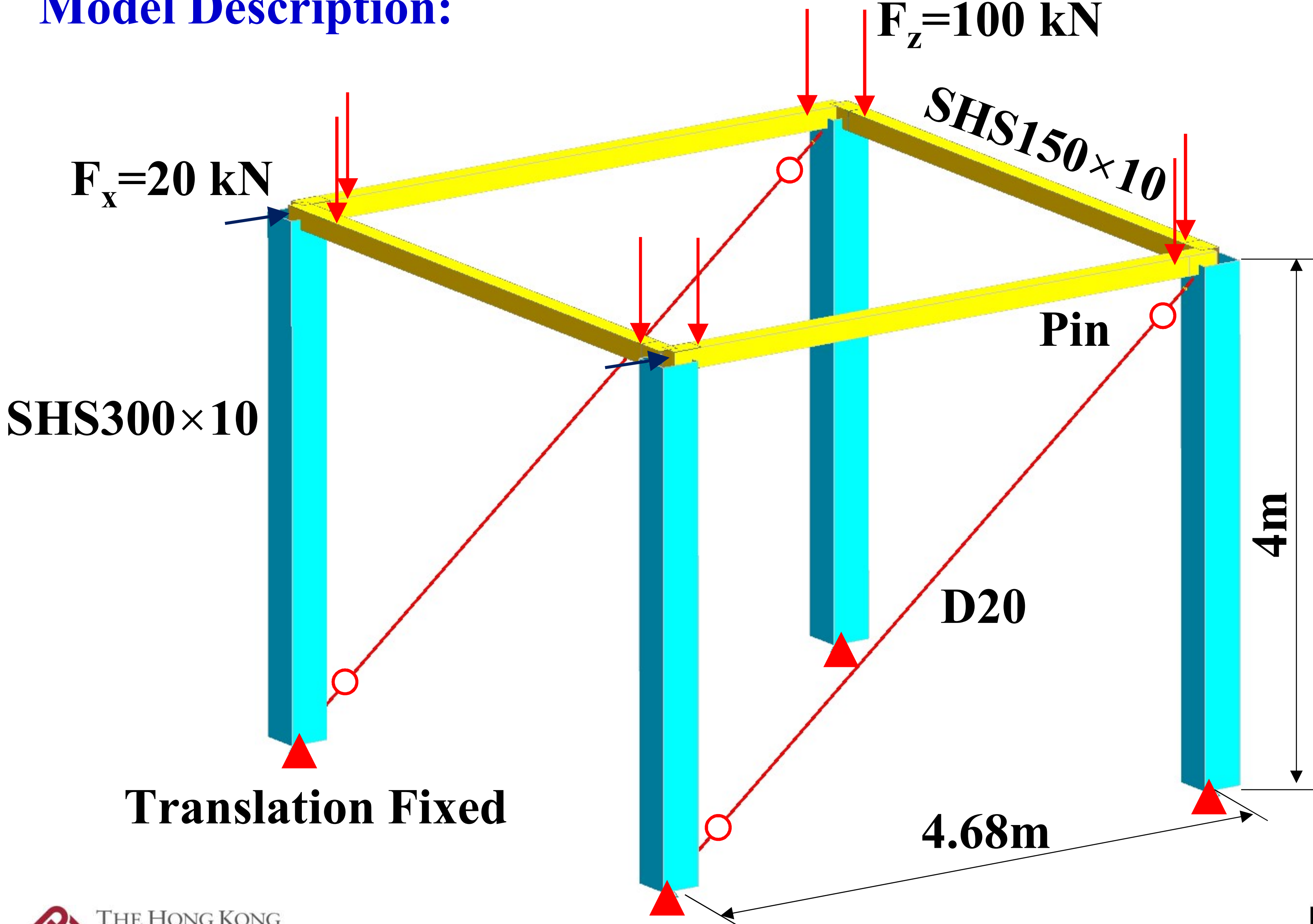
Nida-MNN – A product of Nida family (*BD Reference: S0884*)

- NIDA-MNN is specially developed for nonlinear analysis of cable structures with Moving Node Net, such as rockfall barriers, debris flow barriers.

- NIDA-MNN provides an unified and user-friendly interface to assist the engineers to design a flexible barrier system like conventional steel structures.

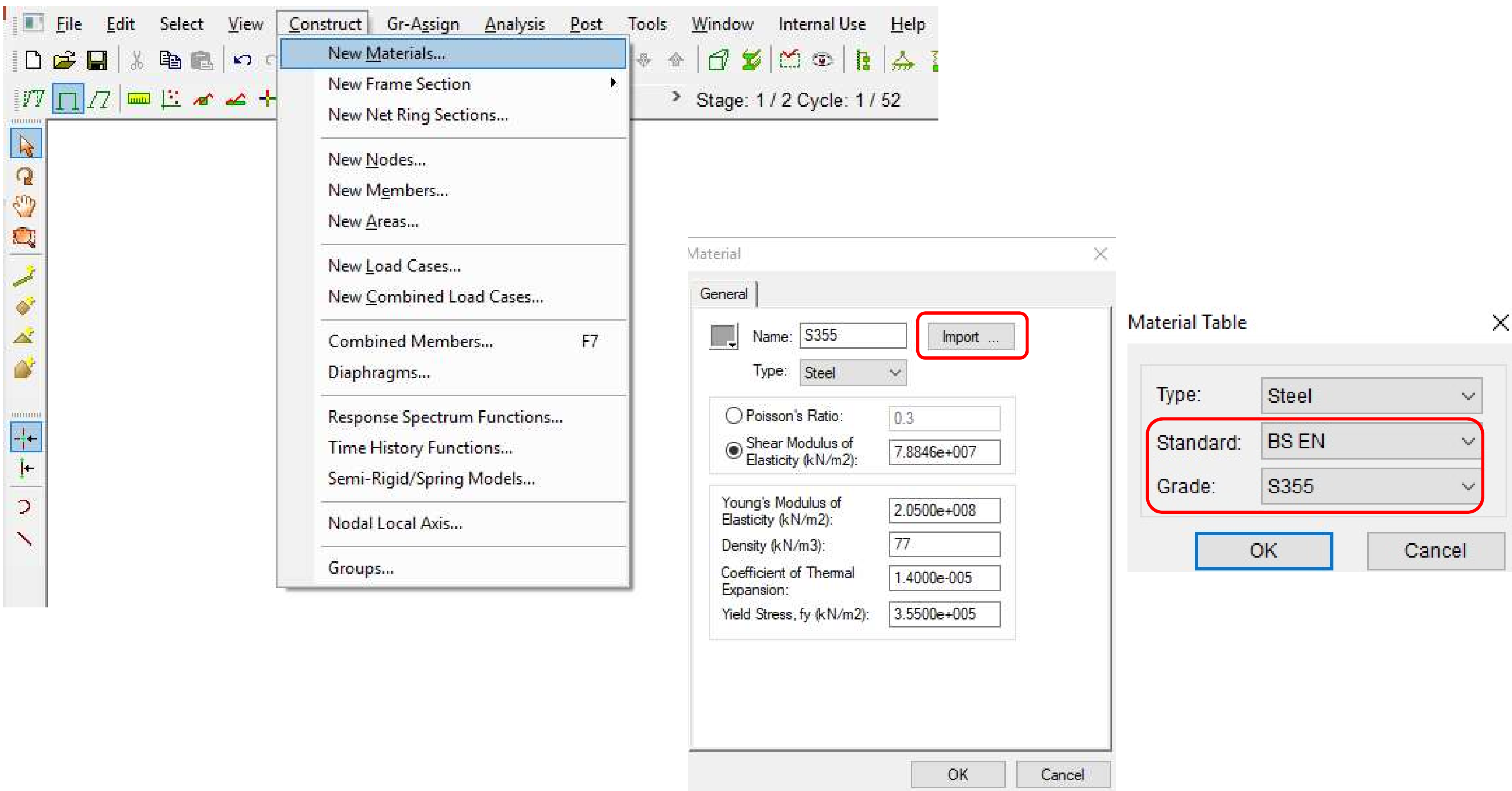
- Unlike the commercial FE software using solid element to simulate flexible barrier, NIDA-MNN uses advanced beam-column element which leads to significant saving of modelling and computational time.

Model Description:

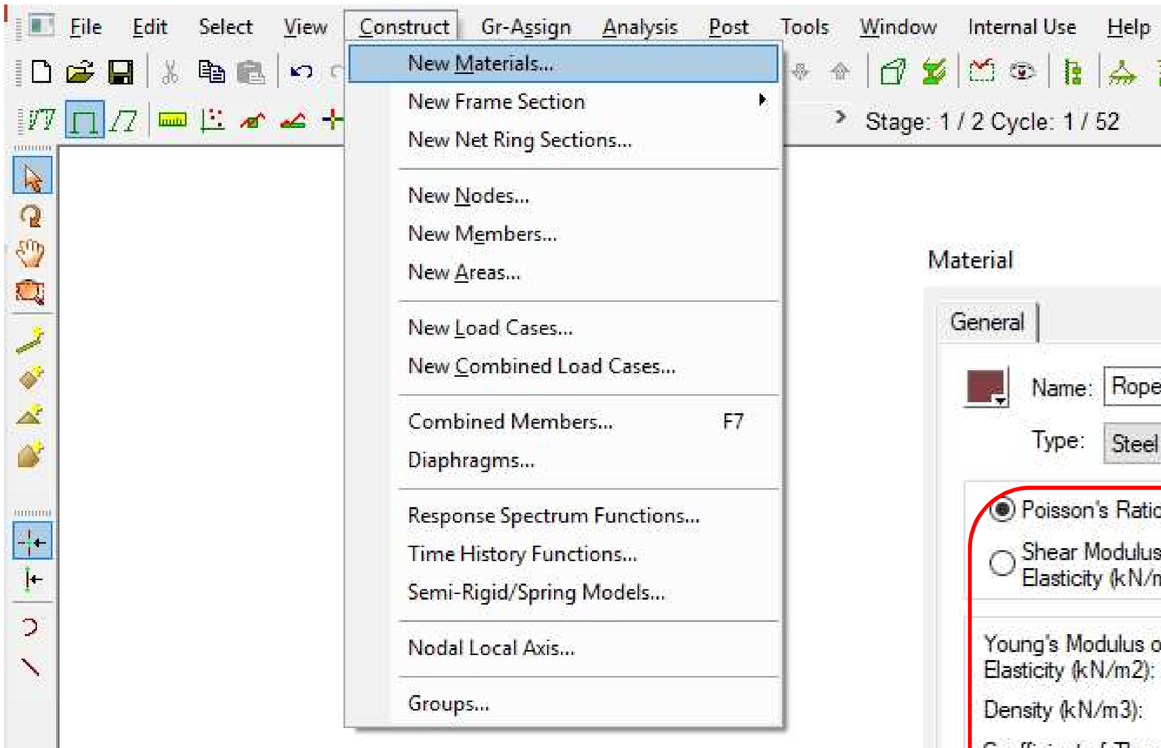


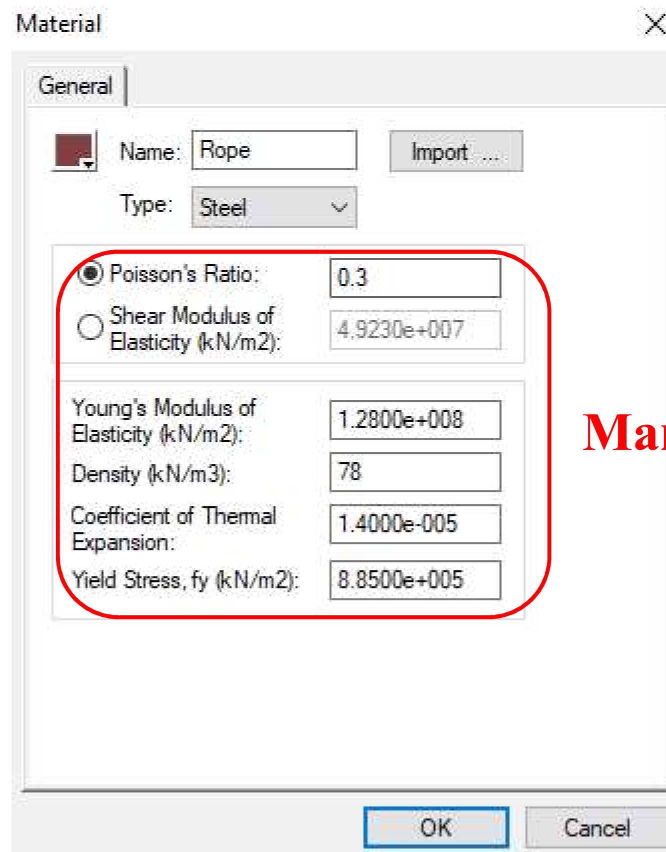
Add Material & Section

Add Material-S355



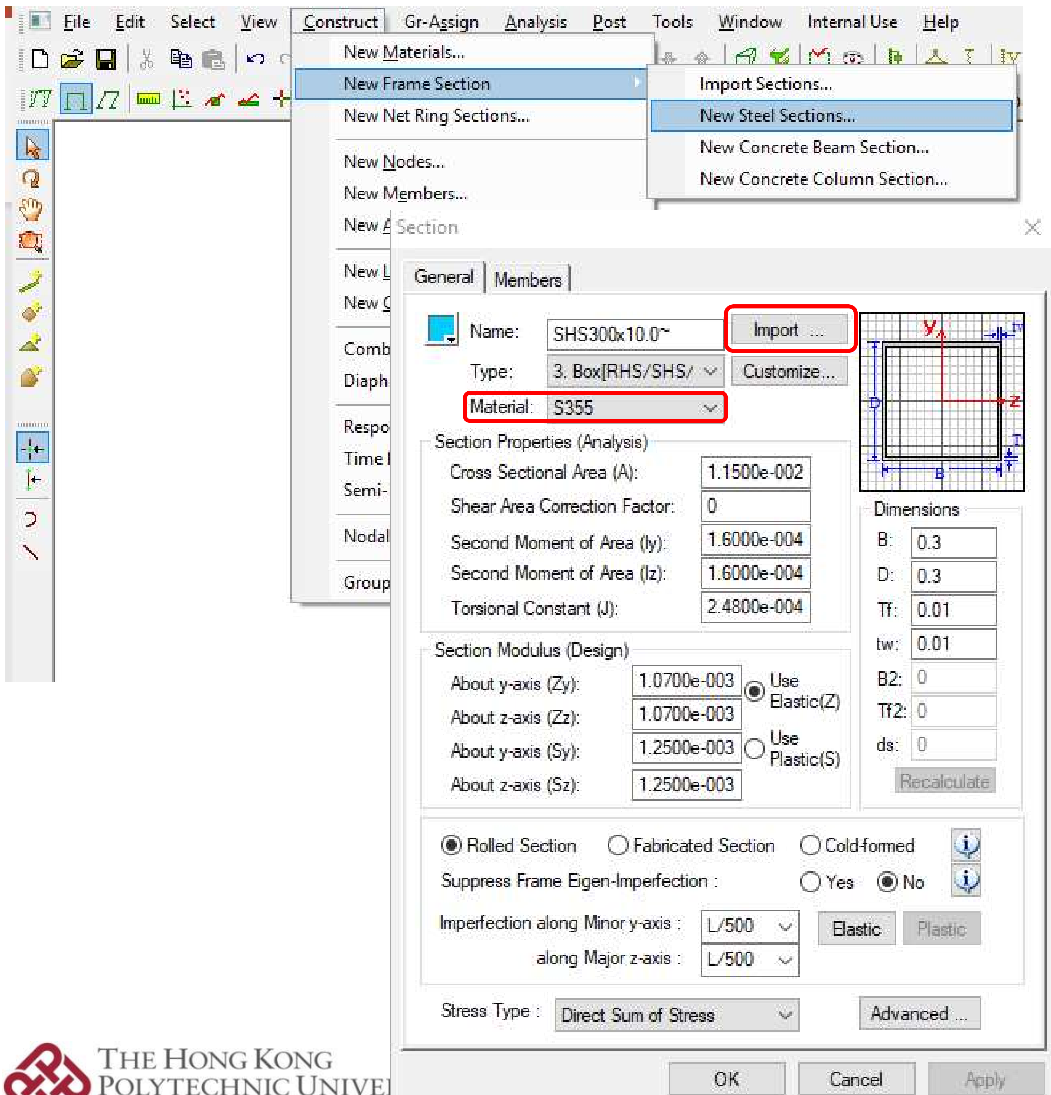
Add Material-Rope

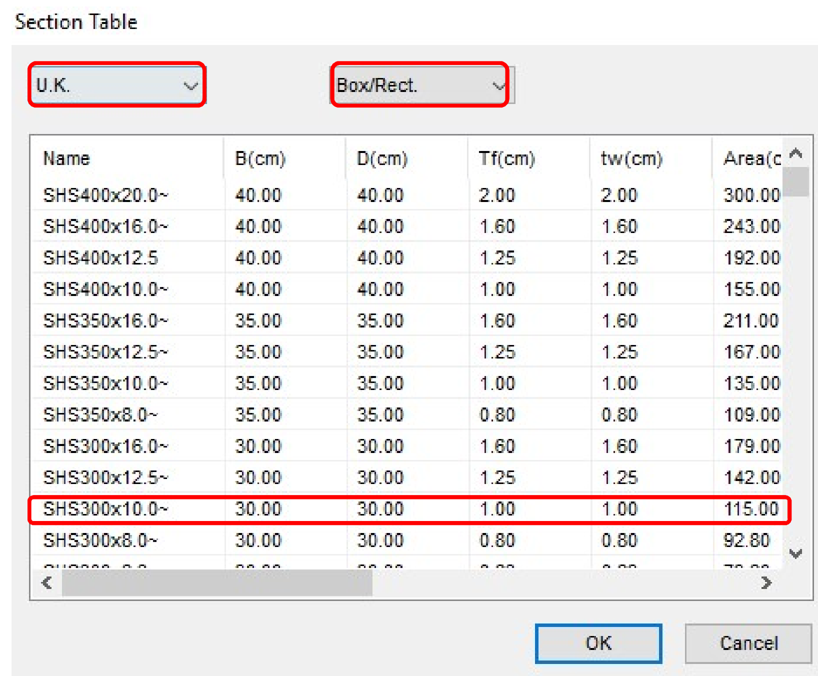




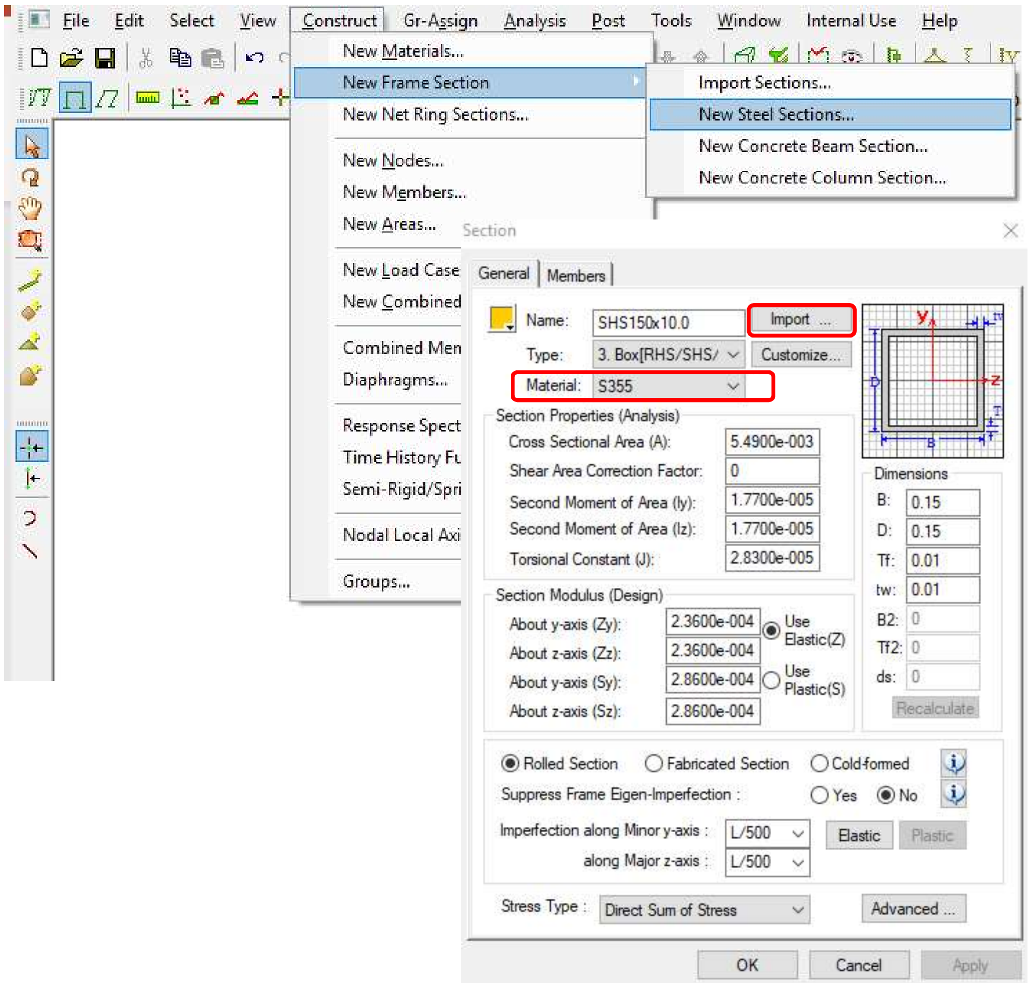
Manual Input

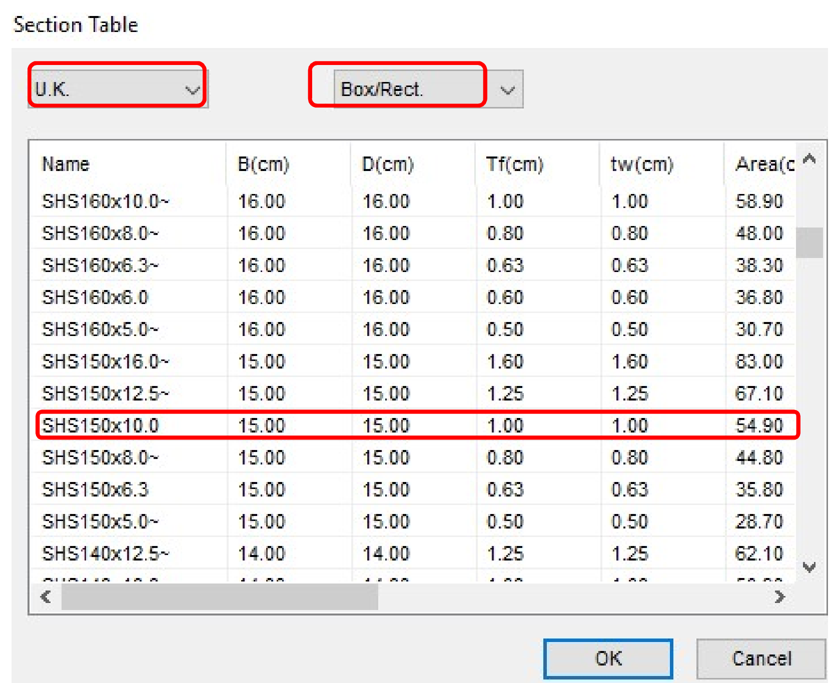
Add Frame Section-SHS300×10 (Column)



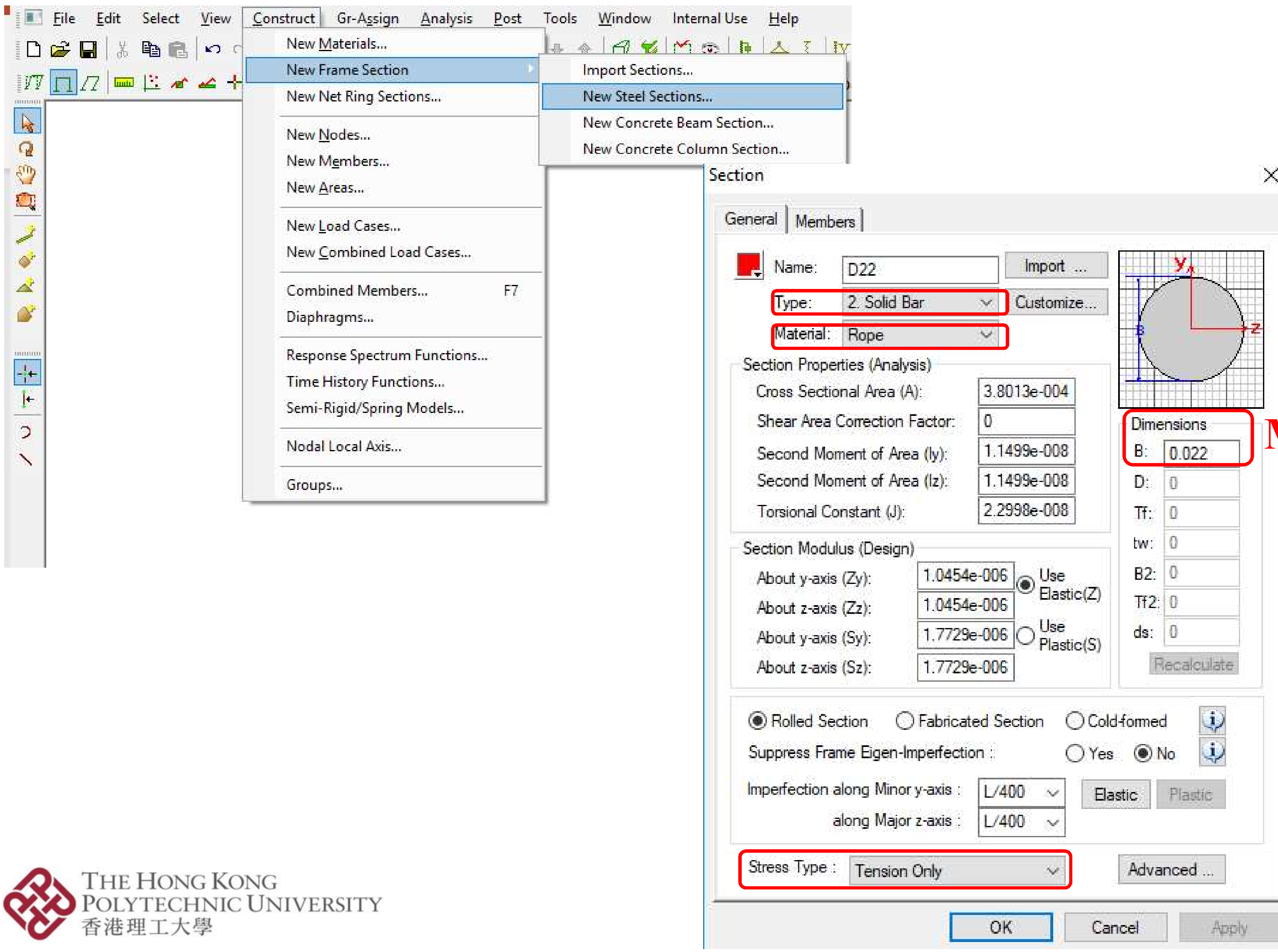


Add Frame Section-SHS150×10 (Beam)





Add Frame Section-D22 (Cable)

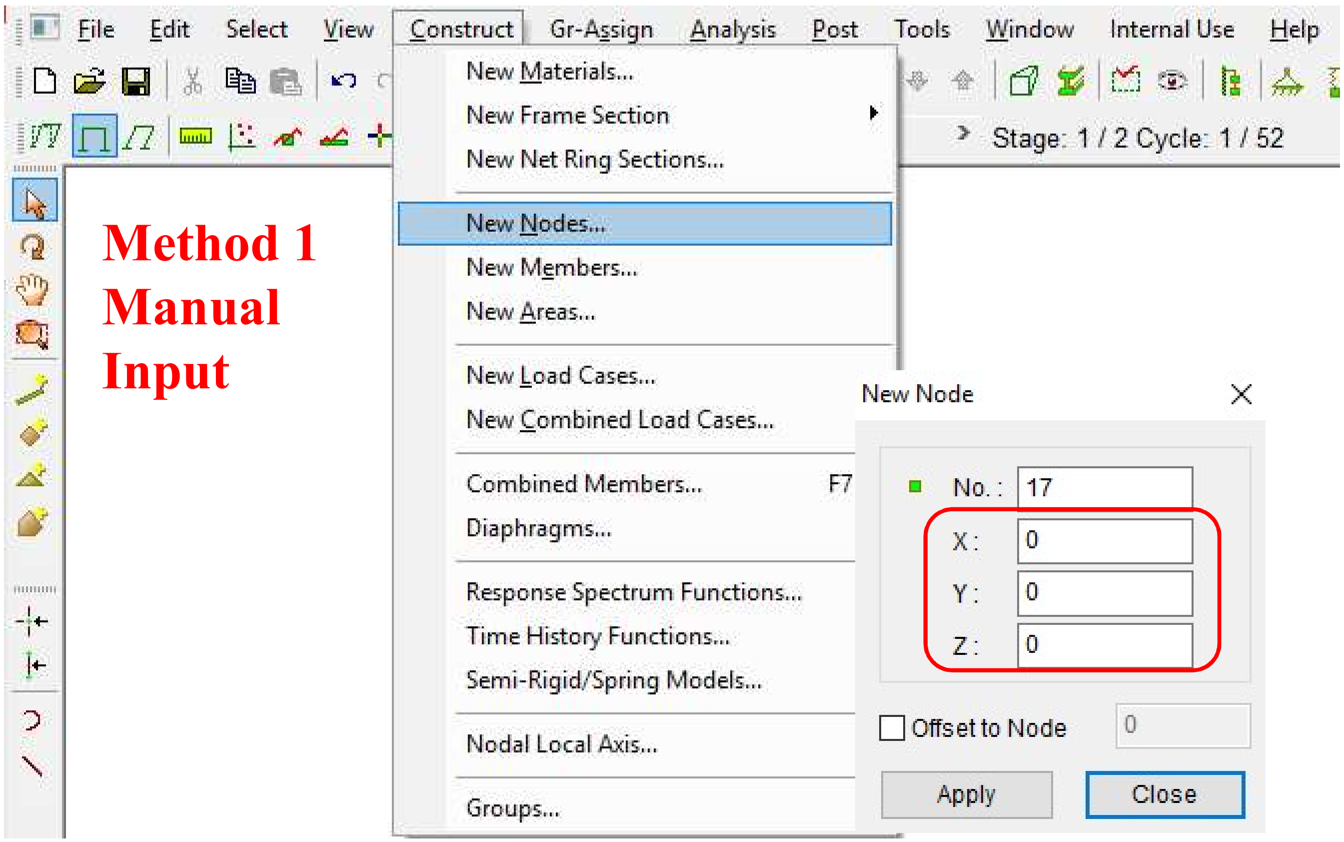


Manual Input

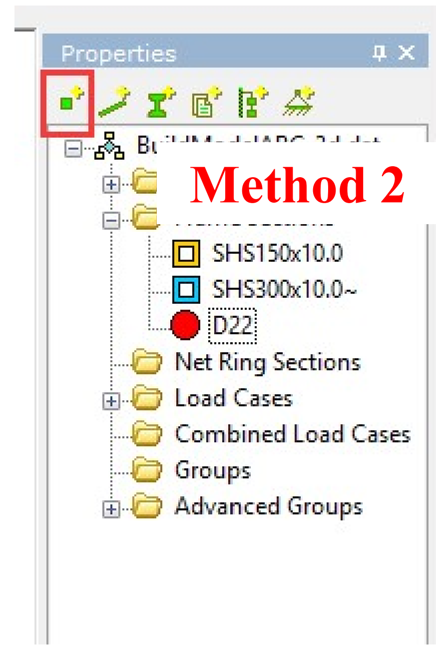
Add Node & Element & Boundary

Add Node

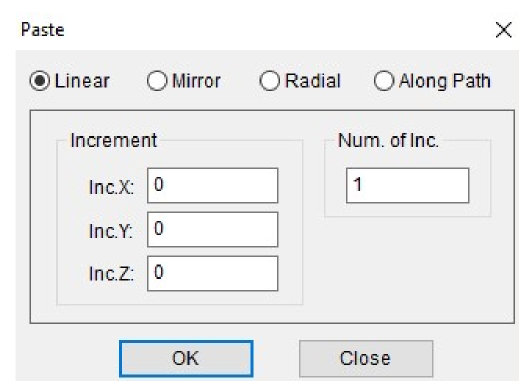
Method 1
Manual Input



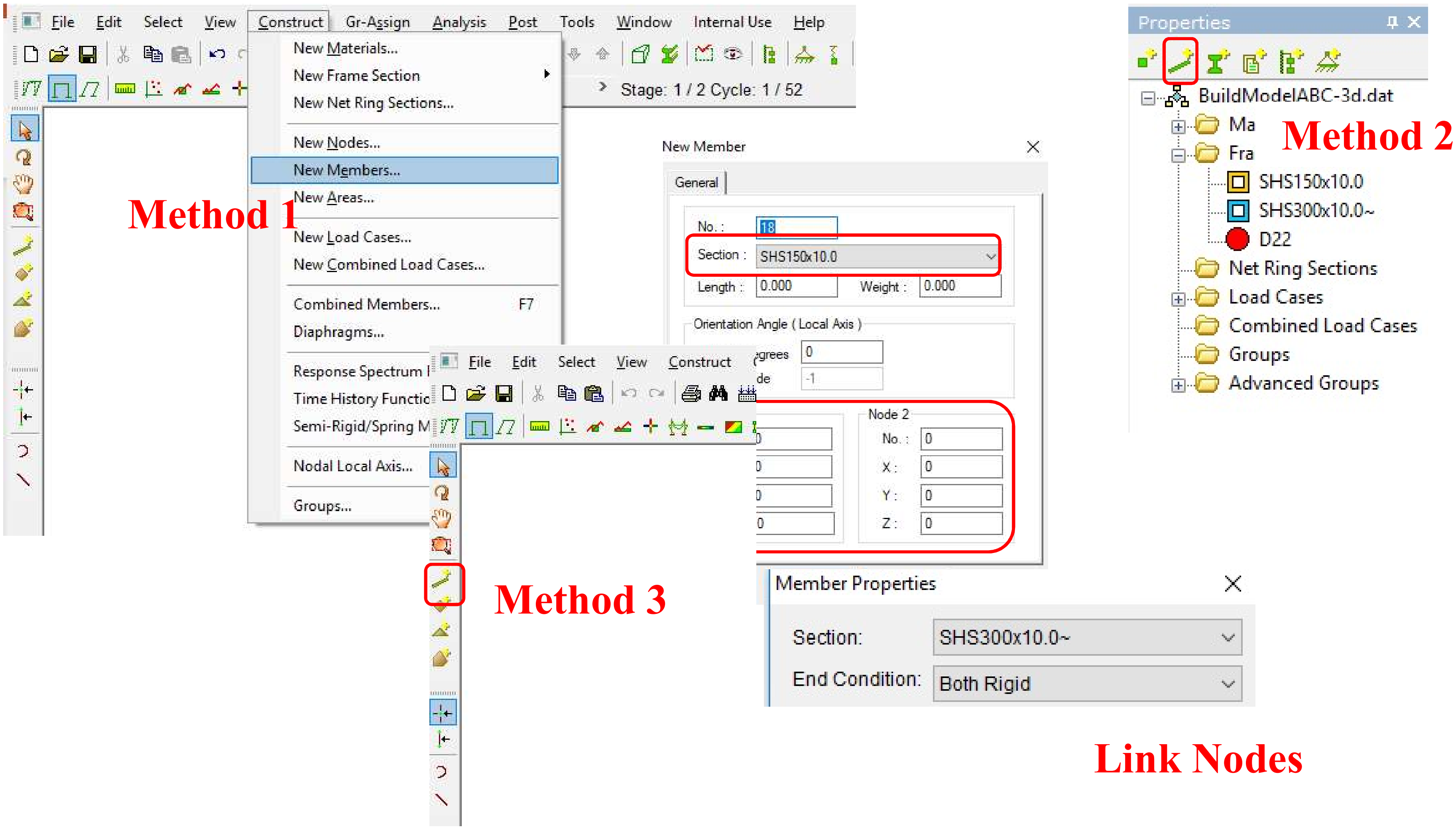
Method 2



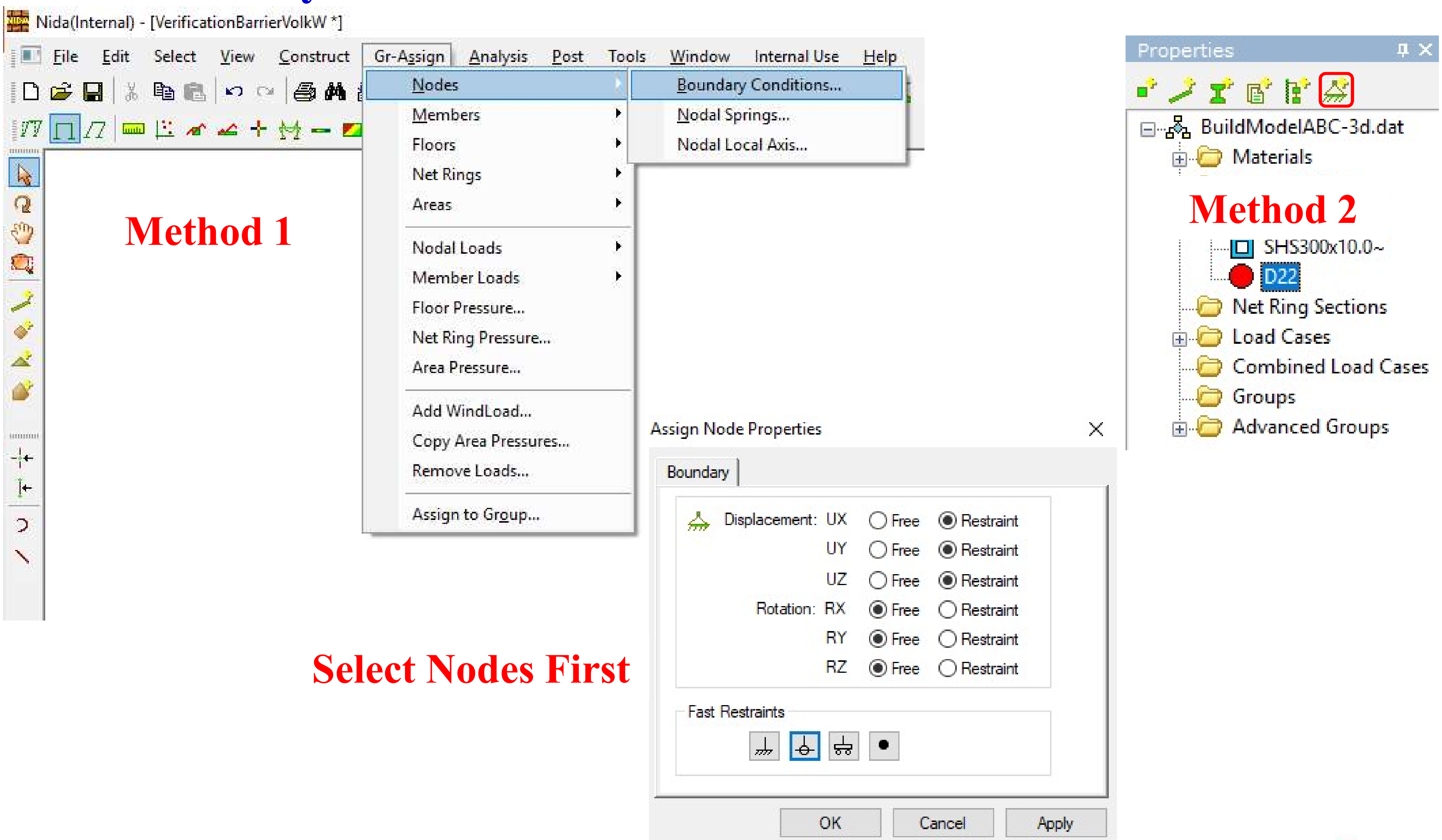
Method 3:
Copy & Paste



Add Member


Method 1
Construct
New Materials...
New Frame Section
New Net Ring Sections...
New Nodes...
New Members...
New Areas...
New Load Cases...
New Combined Load Cases...
Combined Members... F7
Diaphragms...
Nodal Local Axis...
Groups...
Stage: 1 / 2 Cycle: 1 / 52
Method 2
Properties
BuildModelABC-3d.dat
SHS150x10.0
SHS300x10.0~
D22
Net Ring Sections
Load Cases
Combined Load Cases
Groups
Advanced Groups
New Member
General
No. : 18
Section : SHS150x10.0
Length : 0.000
Weight : 0.000
Orientation Angle (Local Axis)
Node 2
Method 3
Member Properties
Section: SHS300x10.0~
End Condition: Both Rigid
Link Nodes

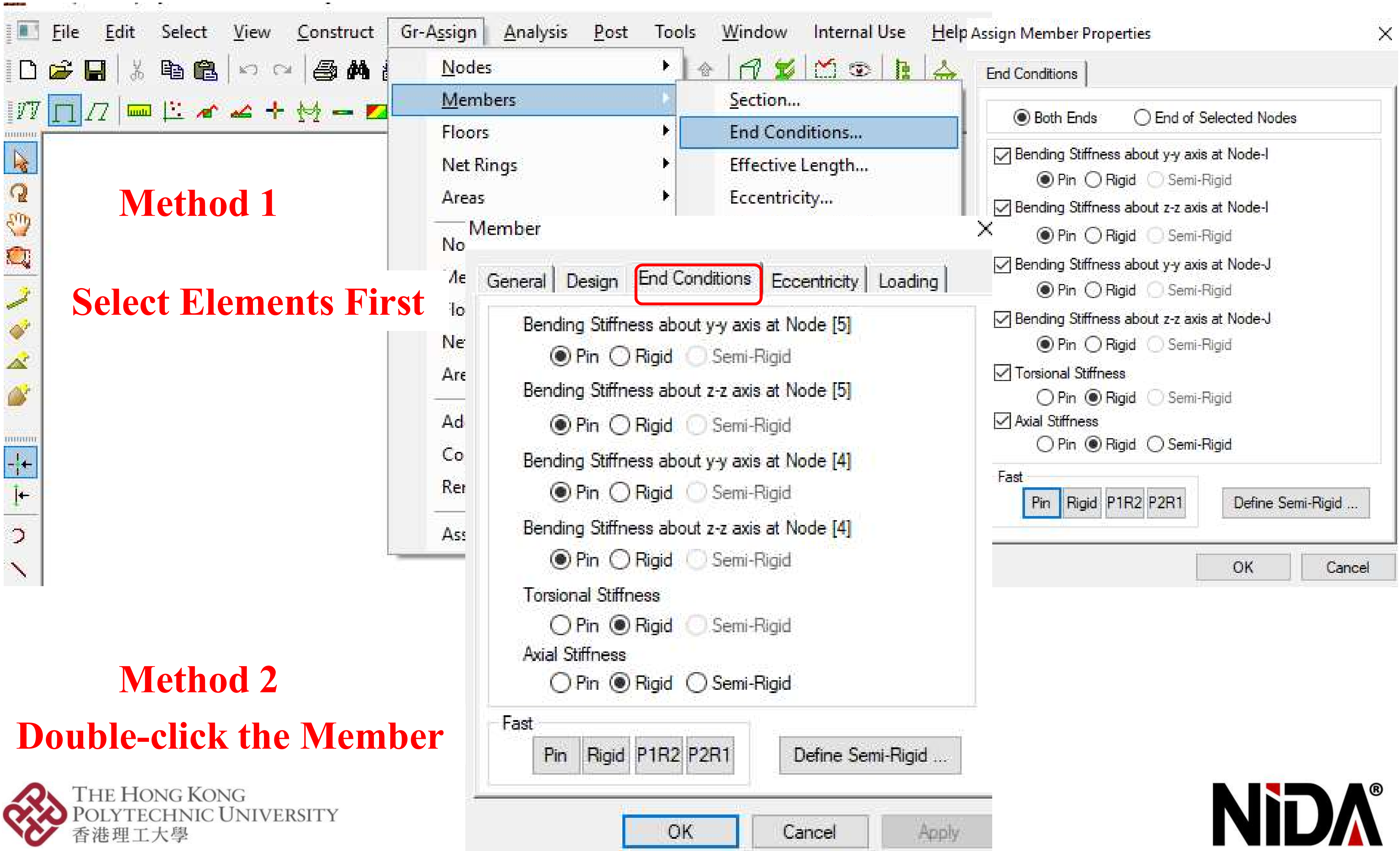
Add Boundary Condition



Set Member End Conditions

Method 1

Select Elements First

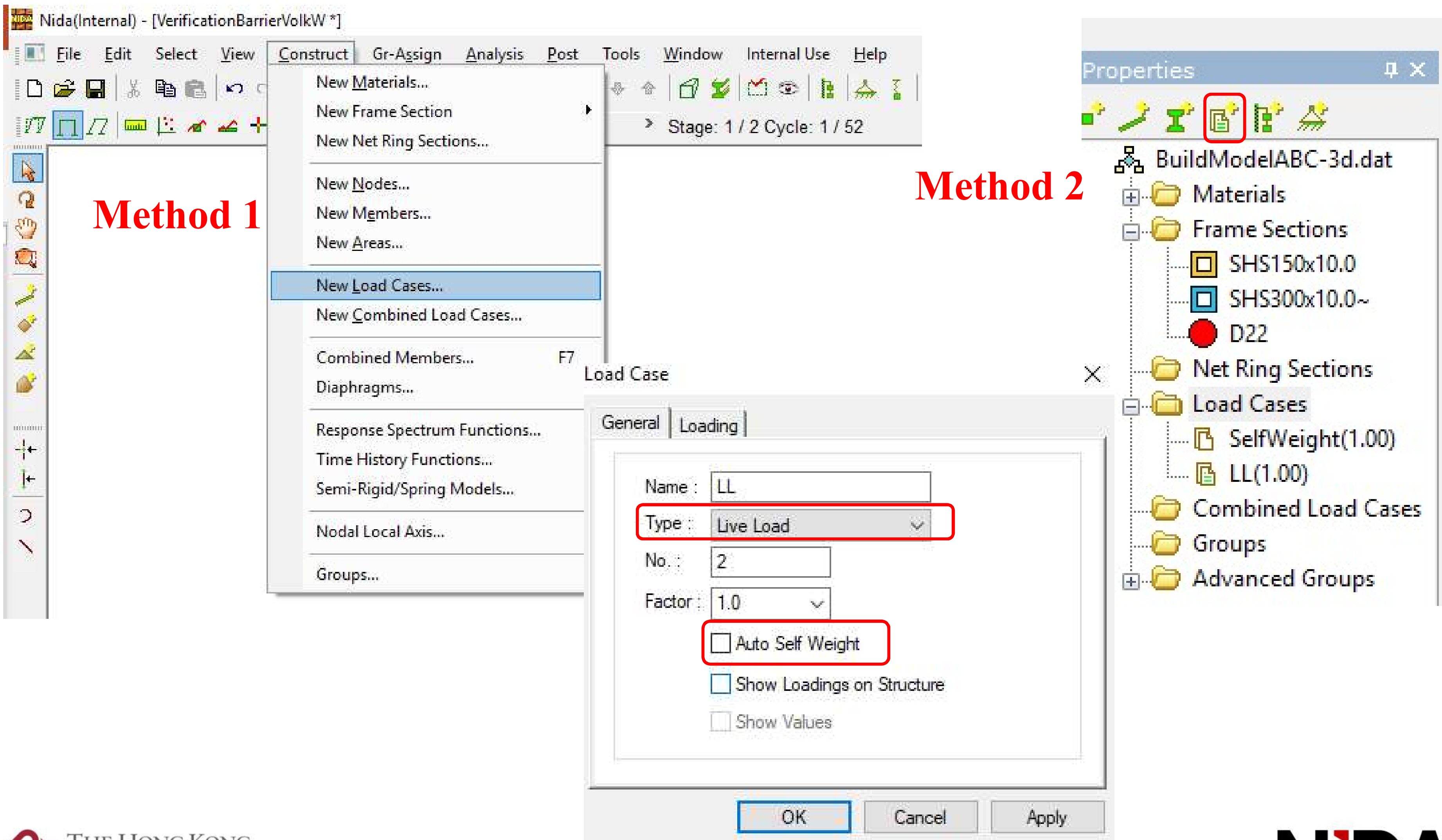


Method 2

Double-click the Member

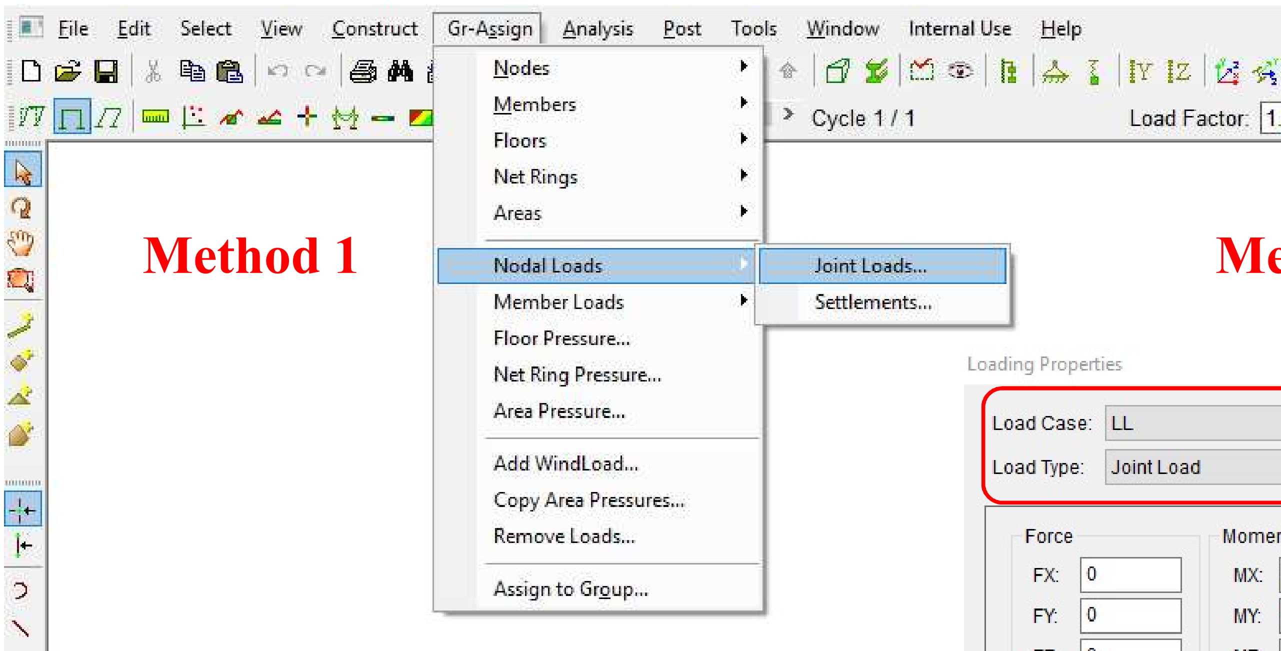
Add Load

Add Load Case



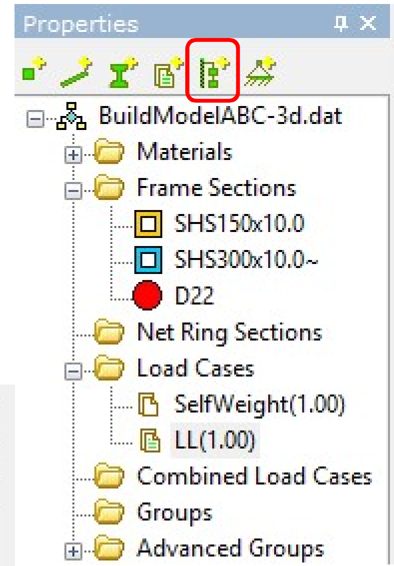
Add Load

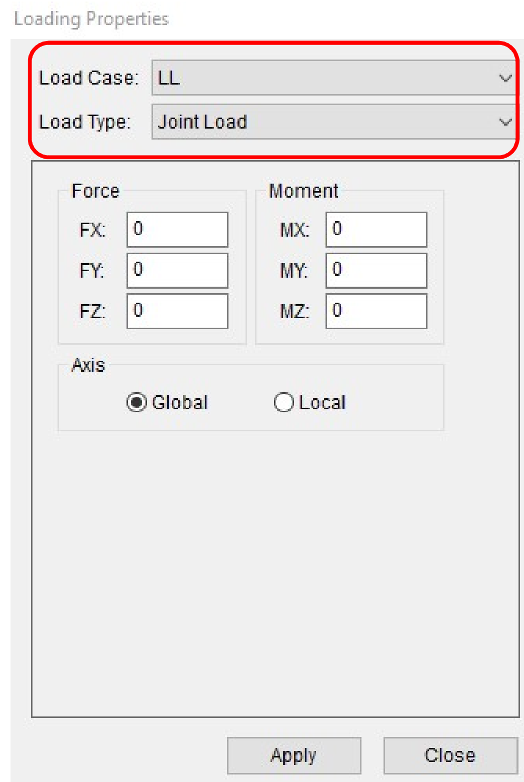
Method 1



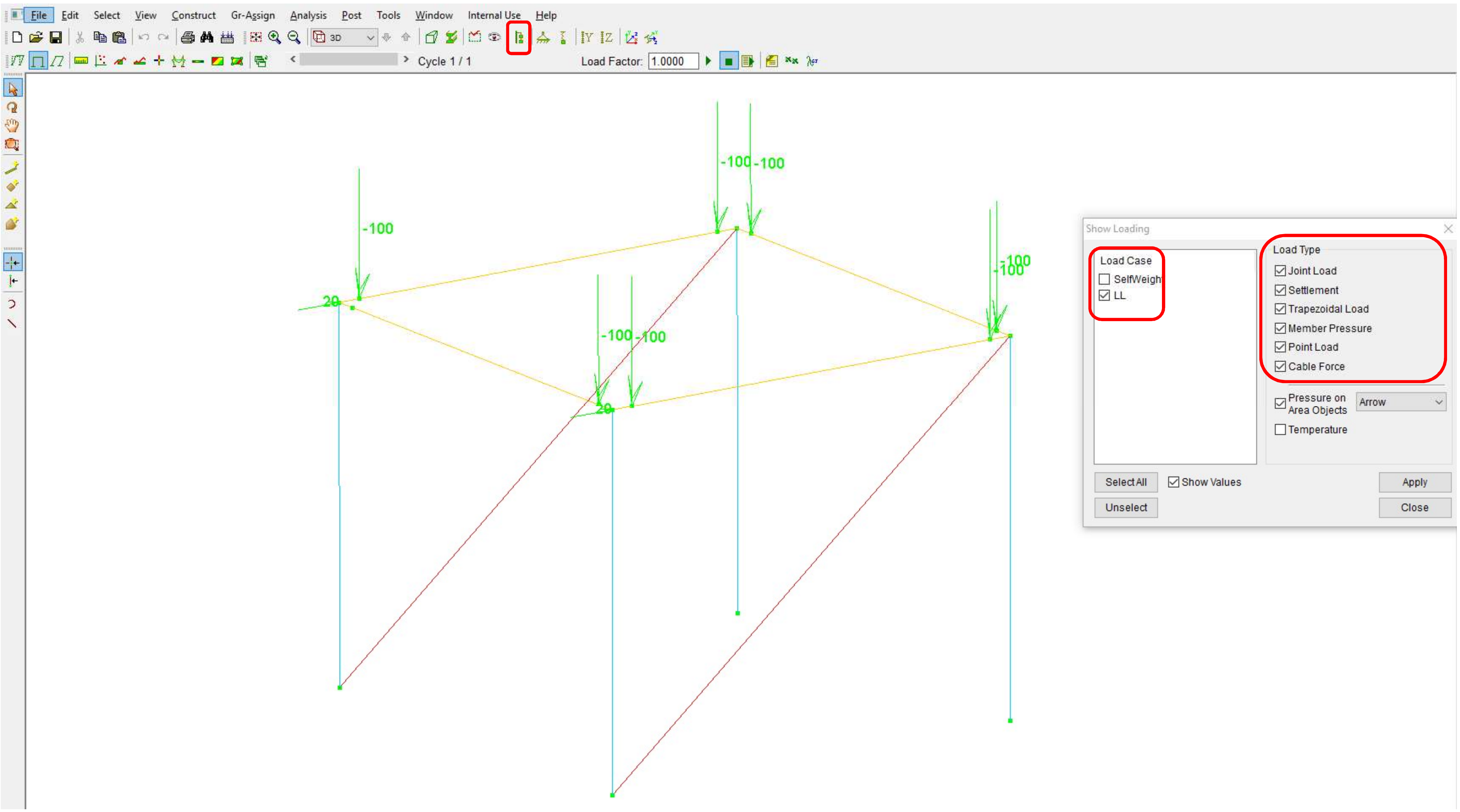
Select Nodes First

Method 2



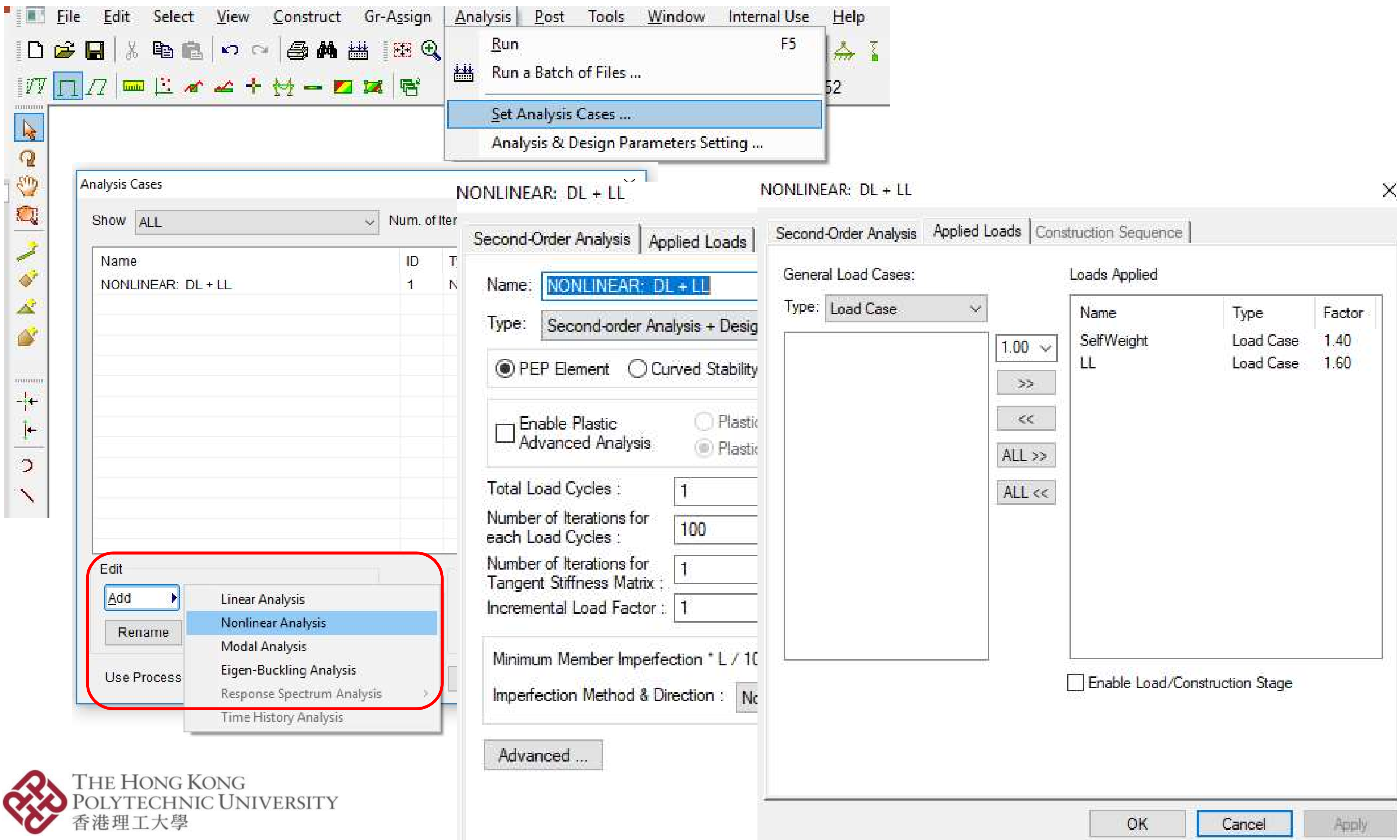


Show Loading



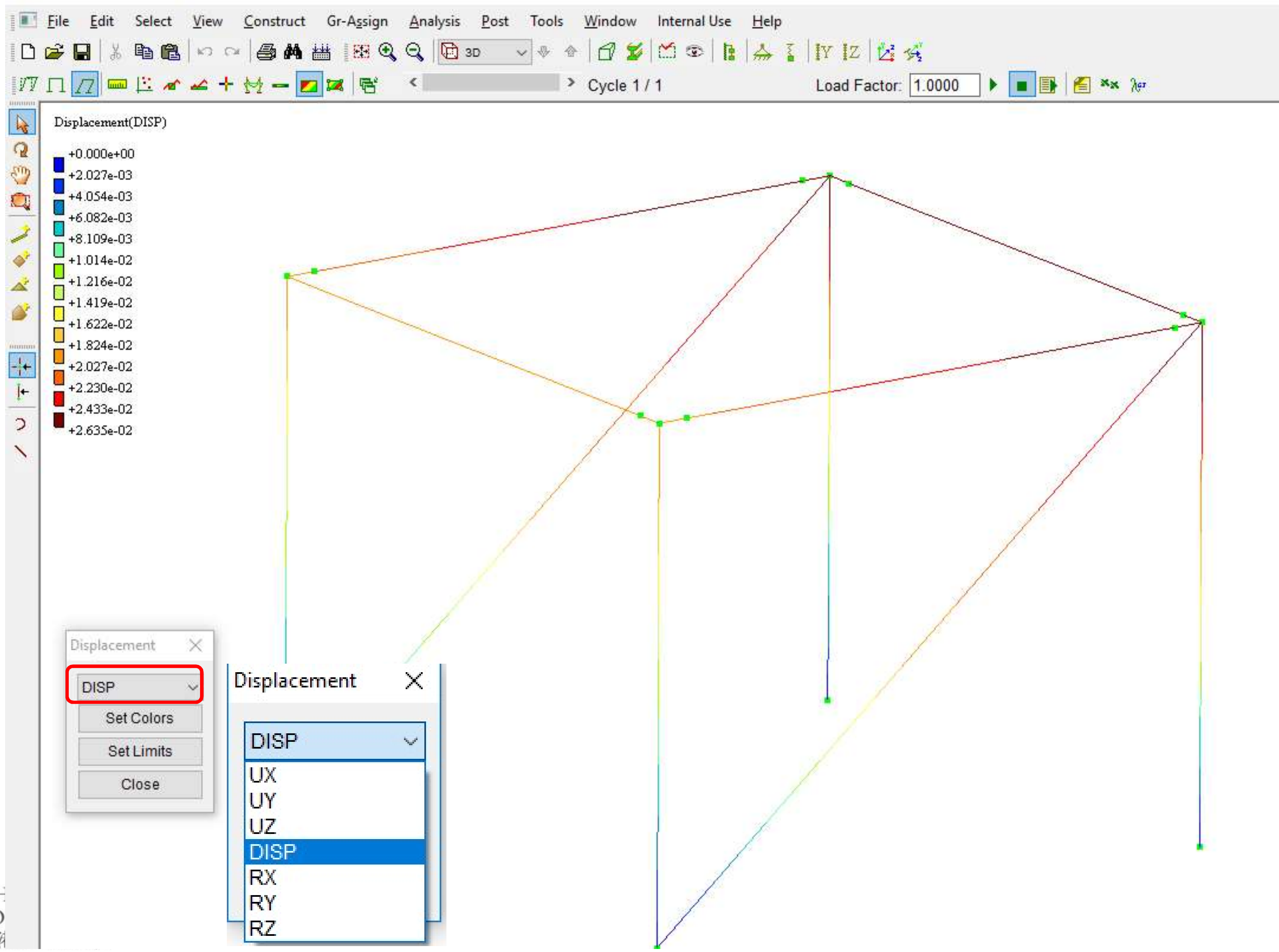
Set Analysis Case

Analysis Case

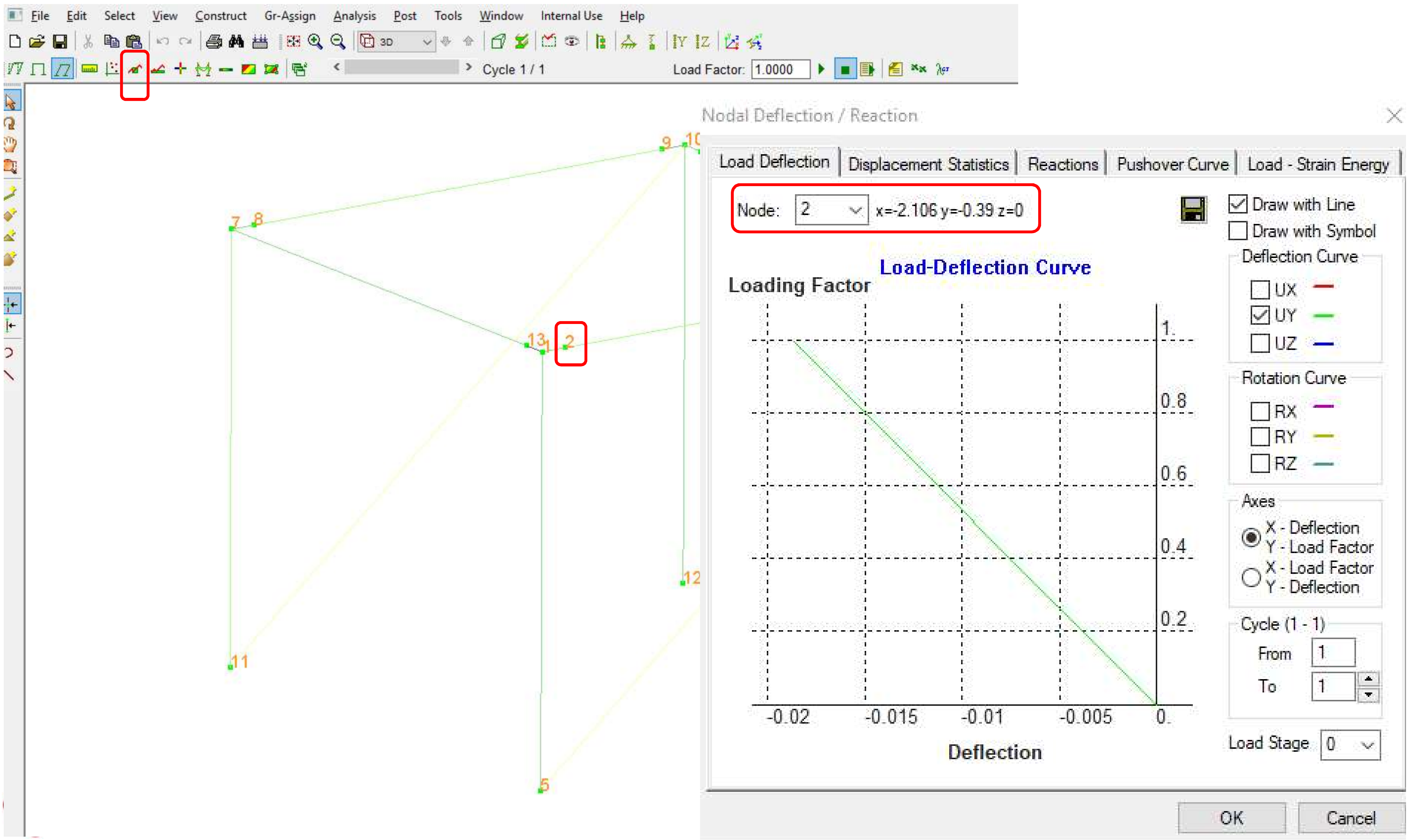


Post

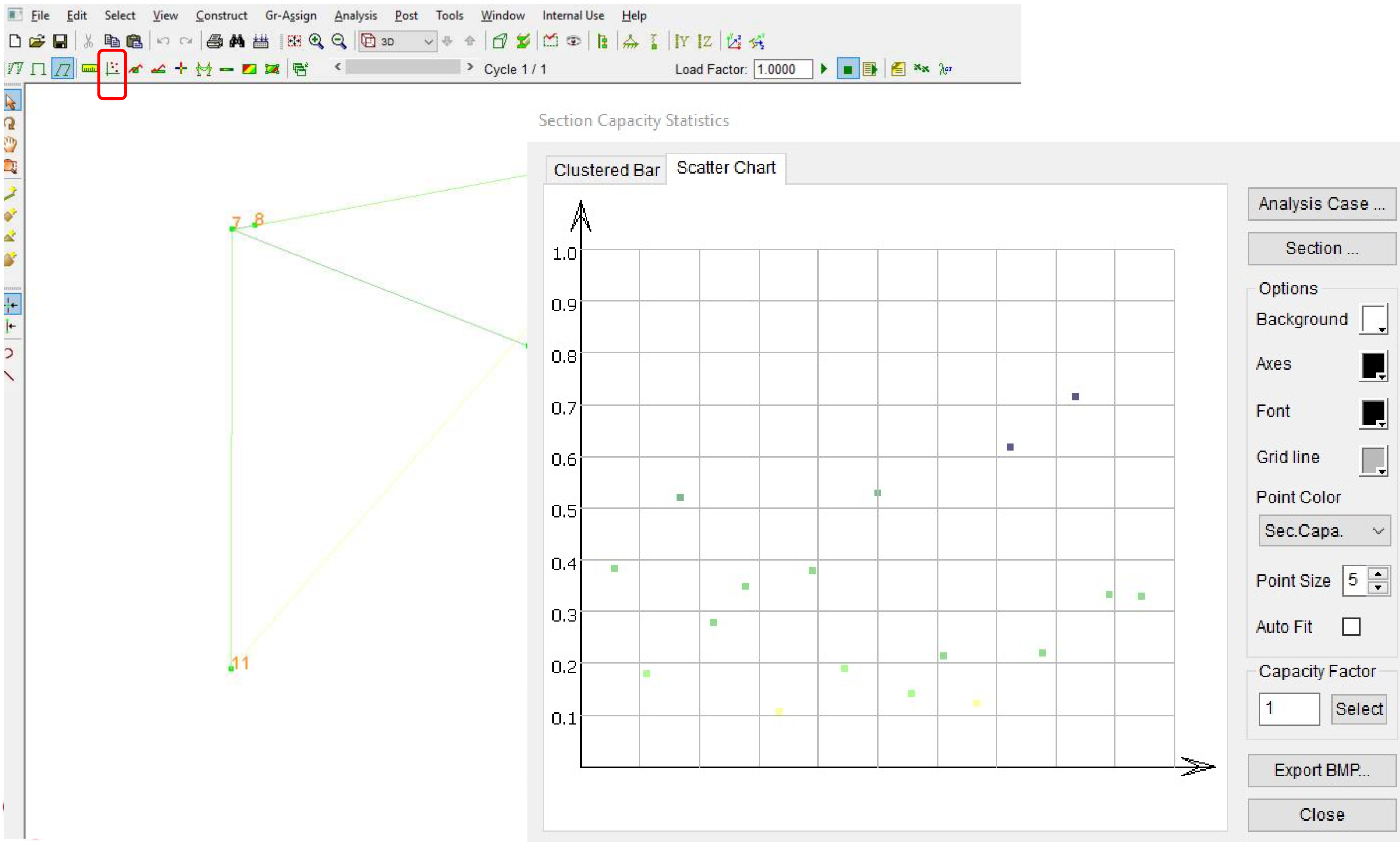
Nodal Displacement Contour



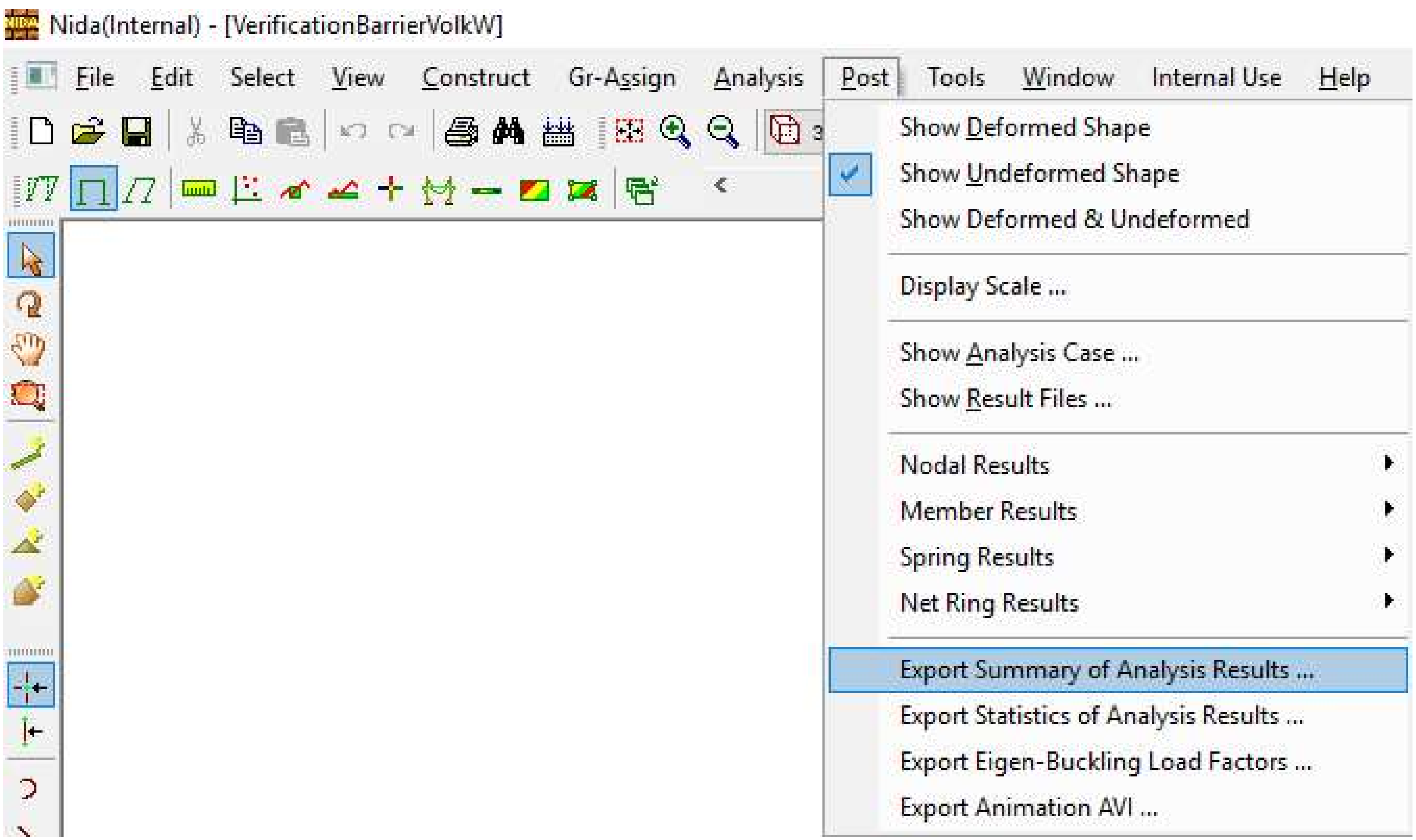
Nodal Deflection



Section Capacity Statistics



Others


Nida(Internal) - [VerificationBarrierVolkW]
File
Edit
Select
View
Construct
Gr-Assign
Analysis
Post
Tools
Window
Internal Use
Help
Show Deformed Shape
Show Undeformed Shape
Show Deformed & Undeformed
Display Scale ...
Show Analysis Case ...
Show Result Files ...
Nodal Results
Member Results
Spring Results
Net Ring Results
Export Summary of Analysis Results ...
Export Statistics of Analysis Results ...
Export Eigen-Buckling Load Factors ...
Export Animation AVI ...

THANK YOU

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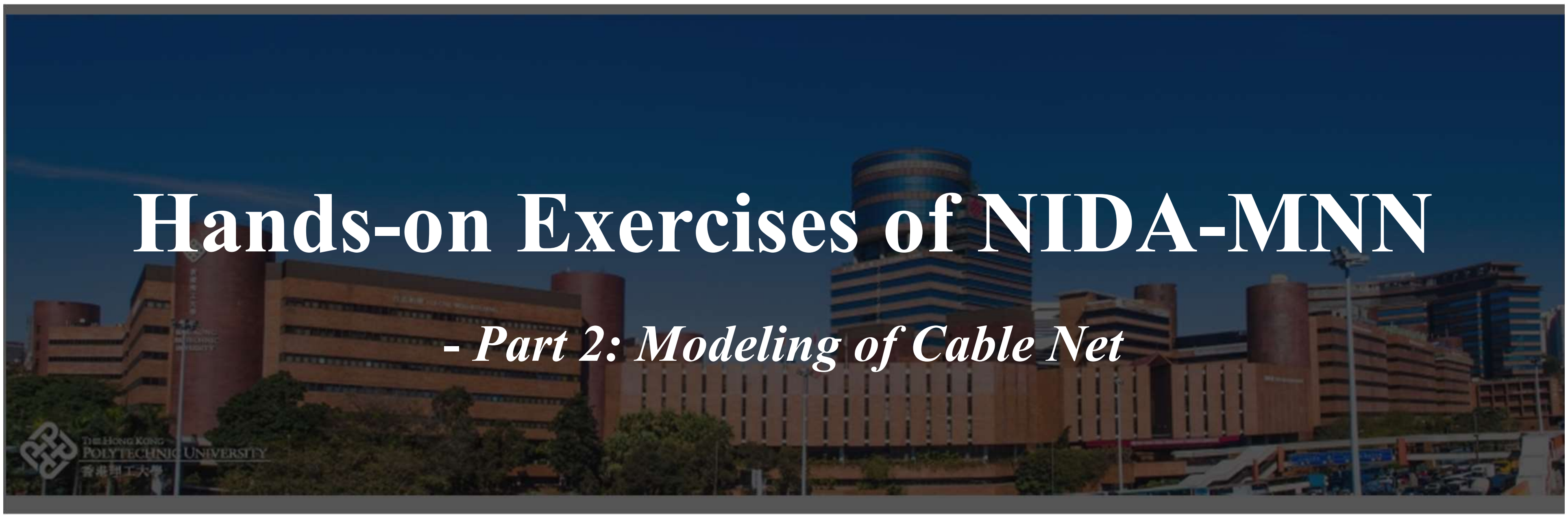
Workshop on Numerical Modelling for Design of Flexible Debris-resisting Barriers

Organized by

Geotechnical Division, Hong Kong Institution of Engineers

Supported by

Department of Civil and Environmental Engineering, The Hong Kong Polytechnic University



Hands-on Exercises of NIDA-MNN

- Part 2: Modeling of Cable Net

Prof. SL Chan, Dr. ZH Zhou, Dr. YP Liu

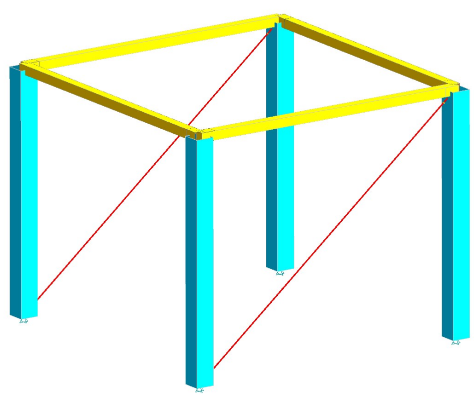
Mr. JW He and Dr. L Zhao

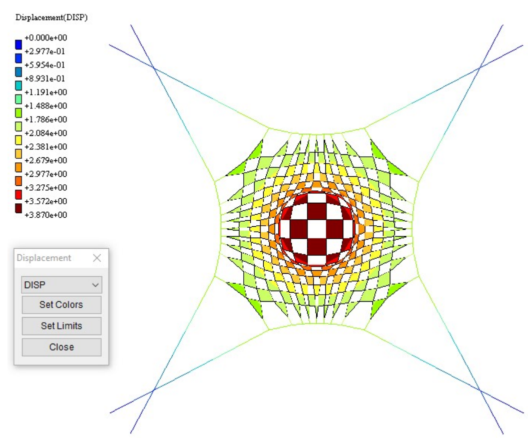
16th April, 2019

The Hong Kong Polytechnic University

Example Detailing

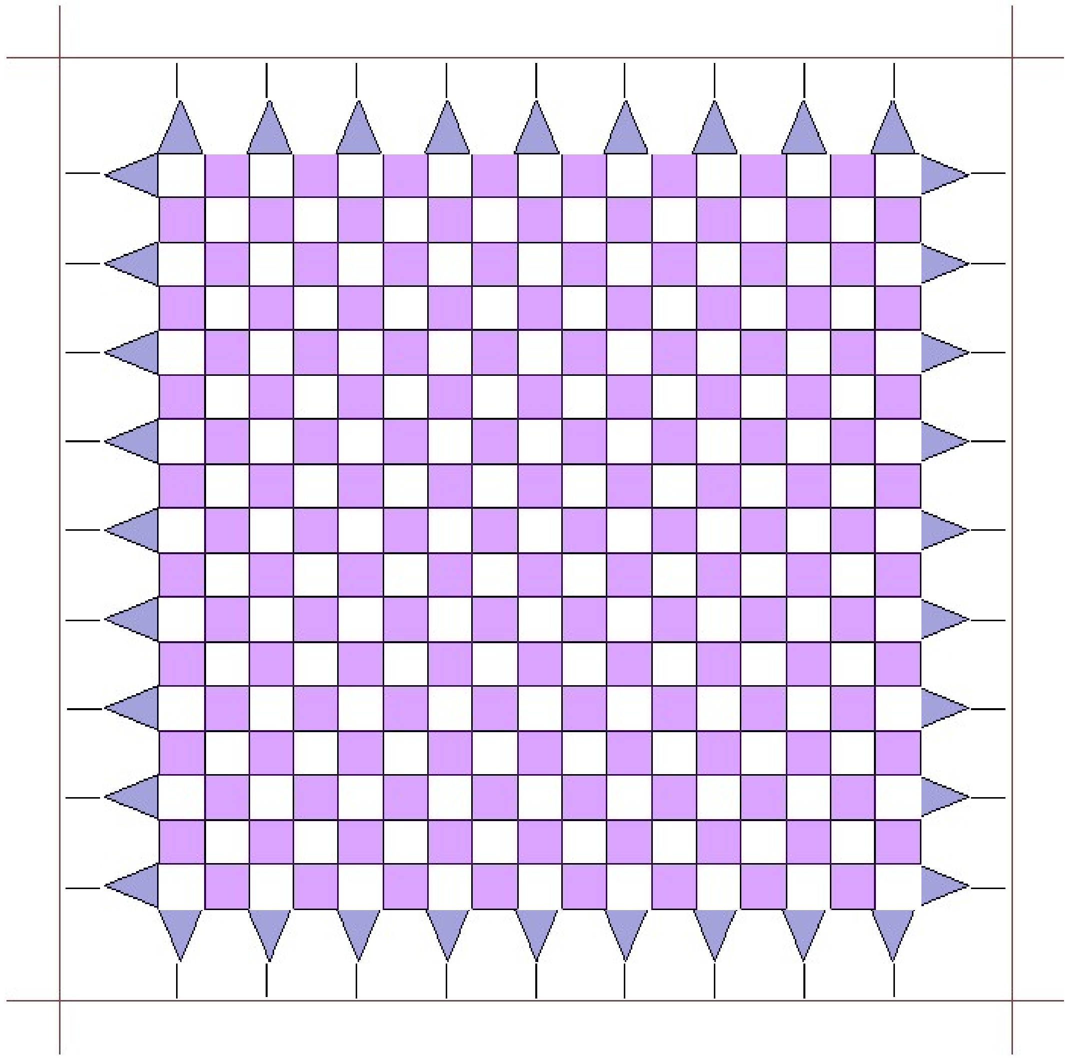
- Basic Operation of NIDA-MNN
- NIDA-MNN Modelling of Cable Net





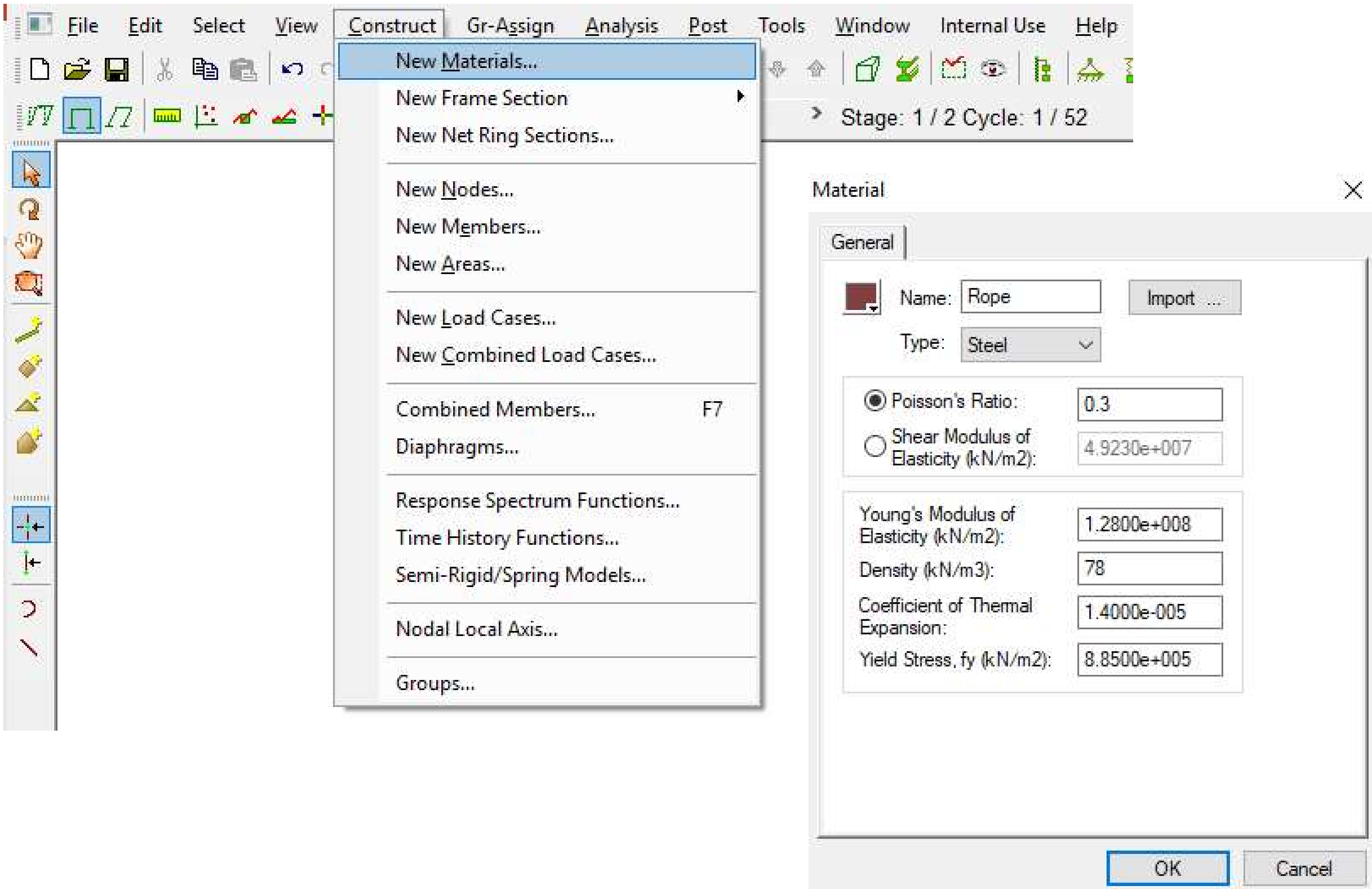
General Description of the model

Model
=
Ropes
+
Centre net
(four-point loading)
+
Side net
(three-point loading)
+
Shackles

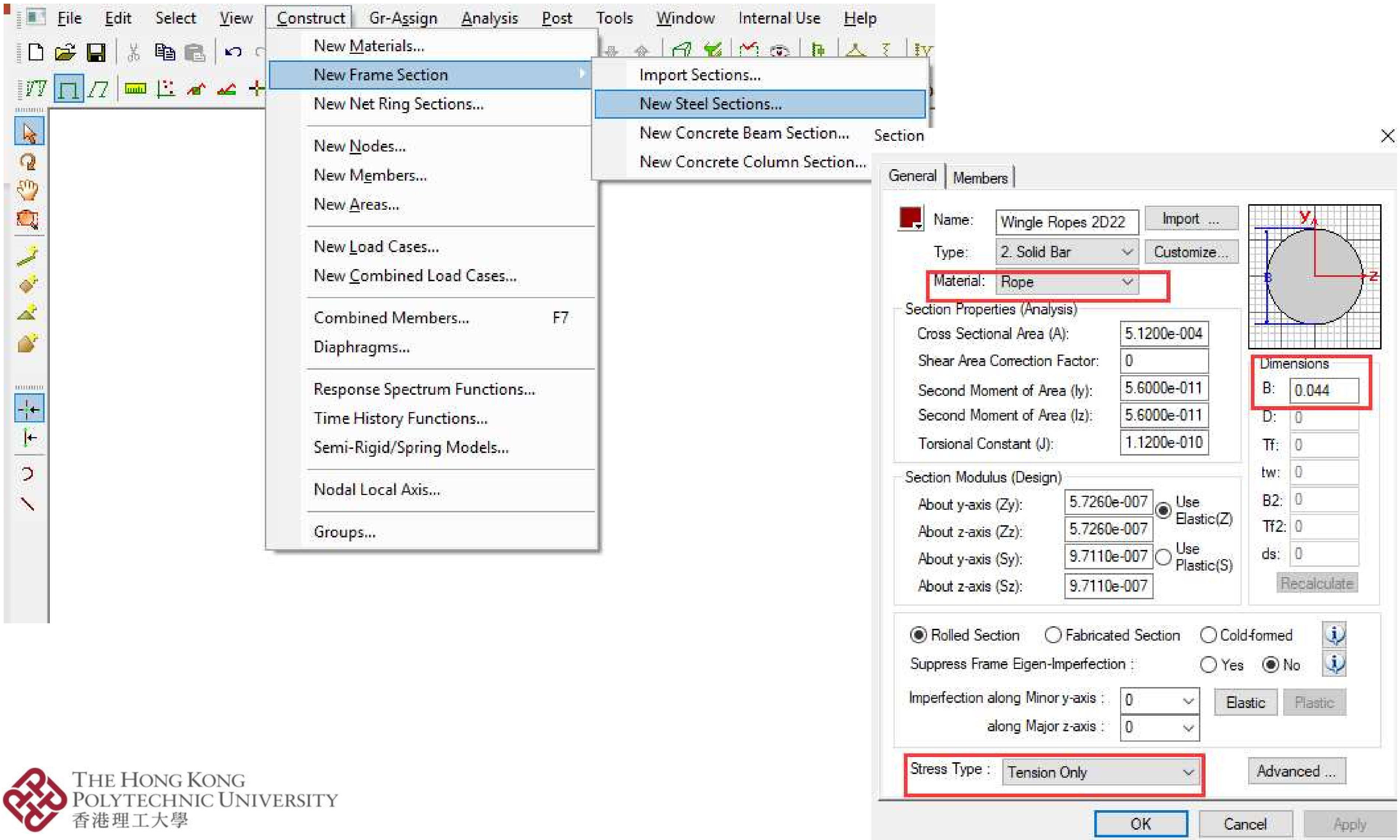


Add Material, Section, Node, Element, Boundary

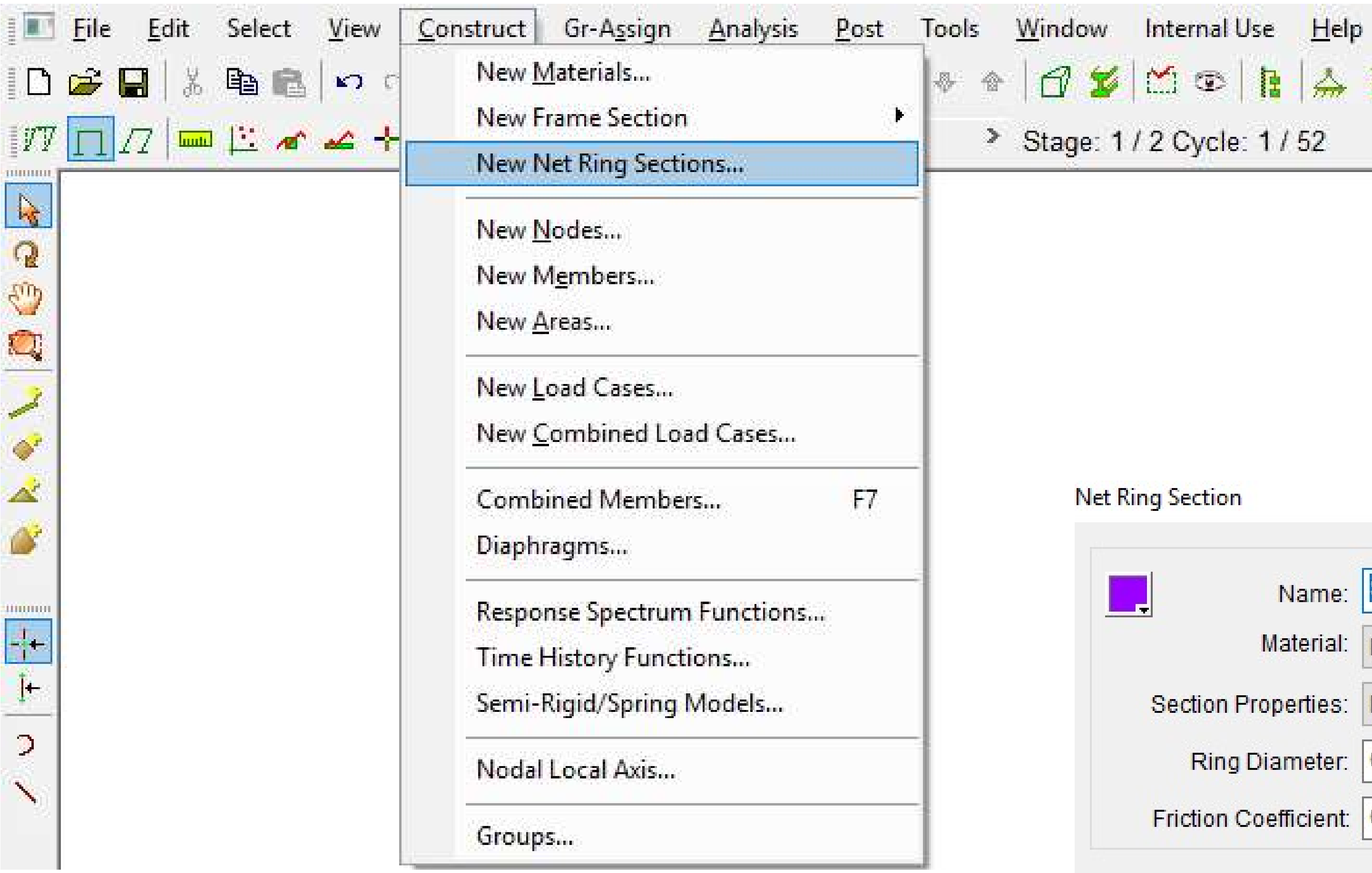
Add Material

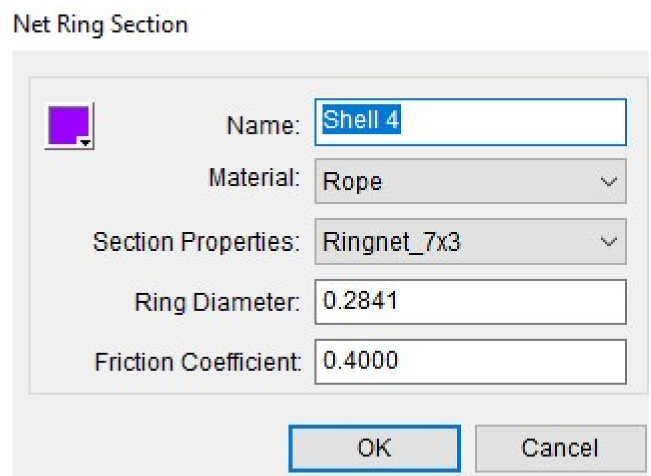


Add Frame Section

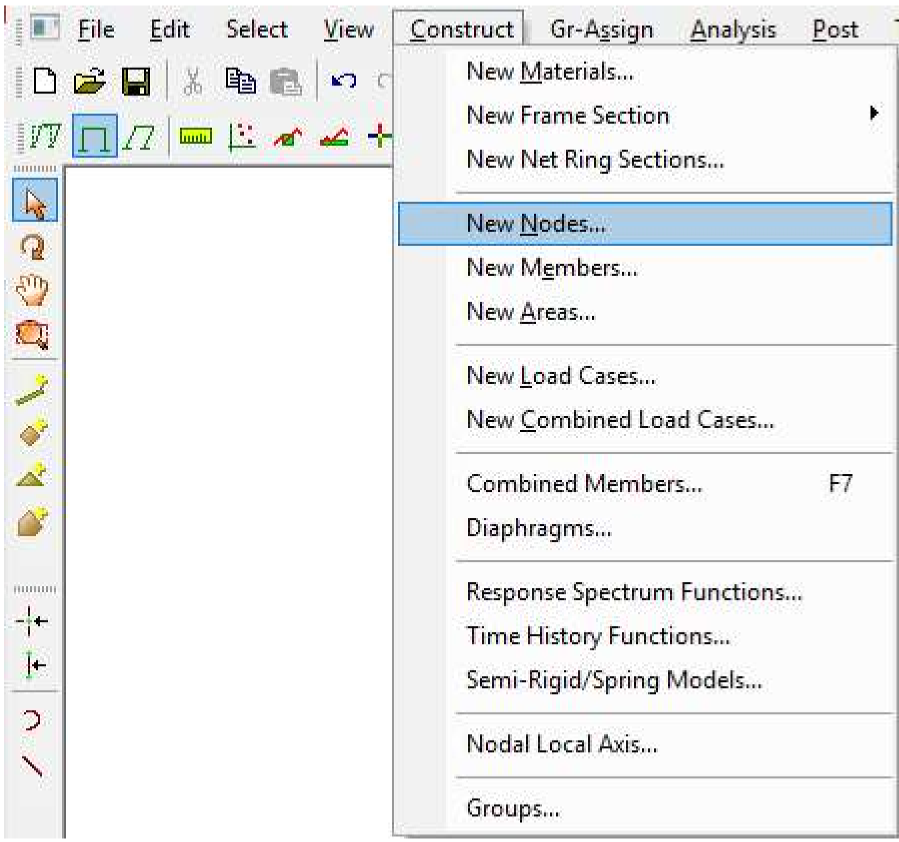


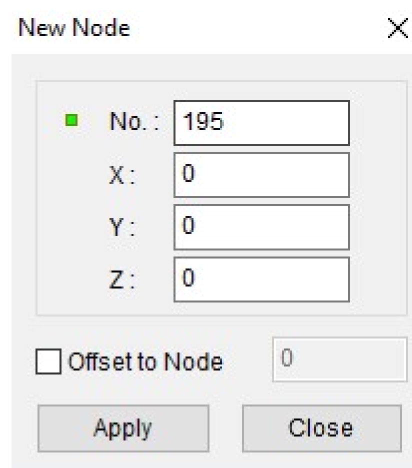
Add Net Ring Section

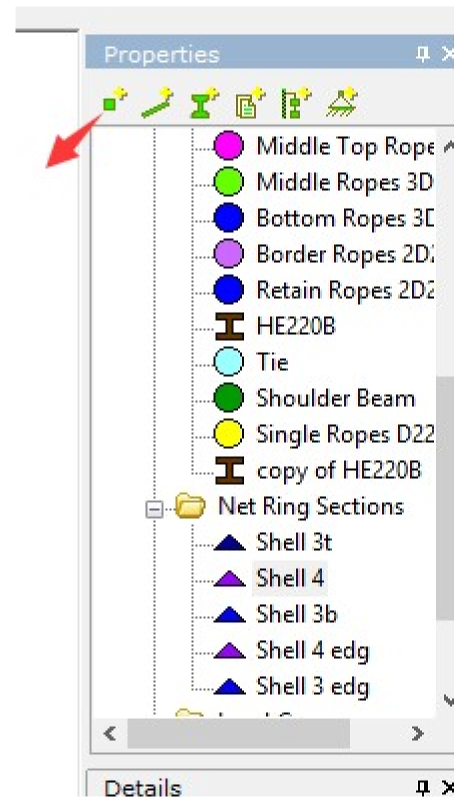




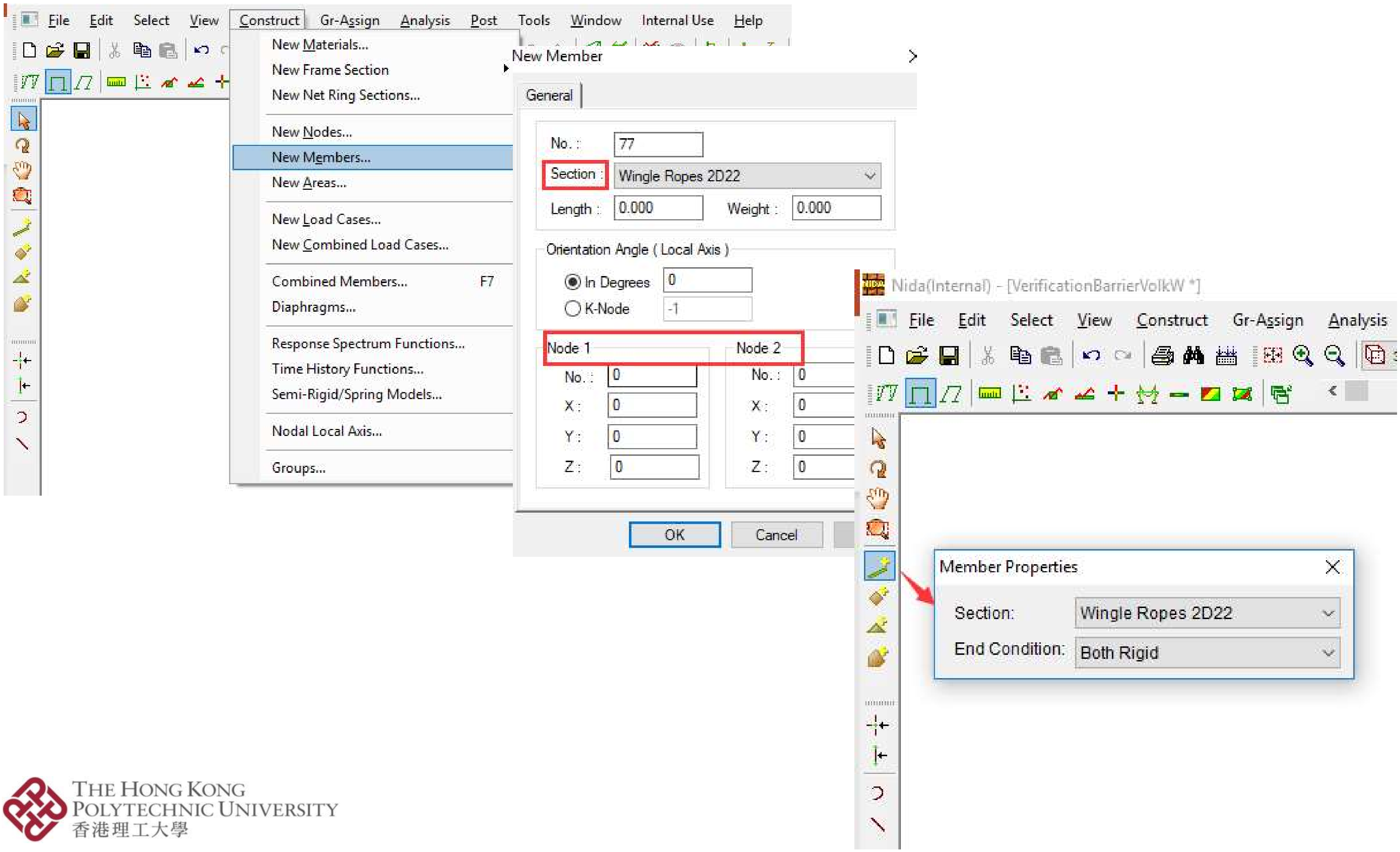
Add Node


File
Edit
Select
View
Construct
Gr-Assign
Analysis
Post
Tools
Window
Internal Use
Help
New Materials...
New Frame Section
New Net Ring Sections...
New Nodes...
New Members...
New Areas...
New Load Cases...
New Combined Load Cases...
Combined Members... F7
Diaphragms...
Response Spectrum Functions...
Time History Functions...
Semi-Rigid/Spring Models...
Nodal Local Axis...
Groups...
Stage: 1 / 2 Cycle: 1 / 52

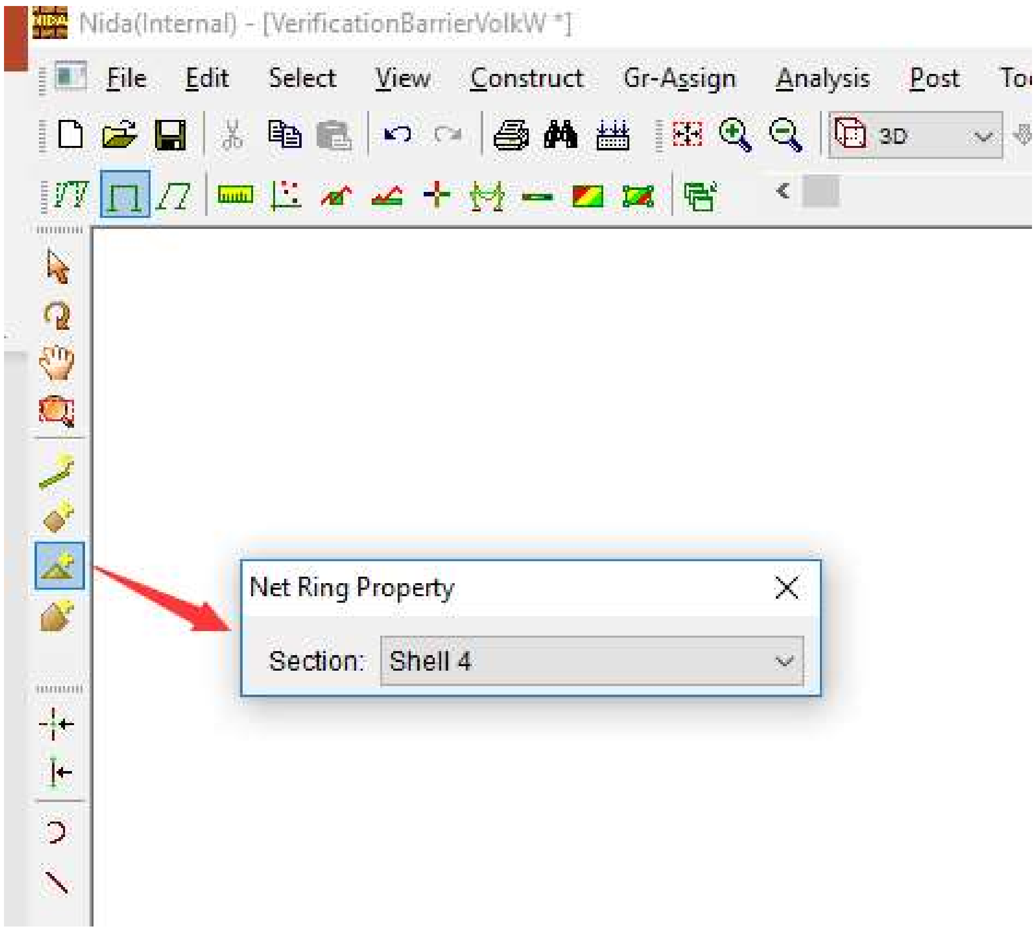

New Node
No. : 195
X : 0
Y : 0
Z : 0
Offset to Node
0
Apply
Close


Properties
Middle Top Rope
Middle Ropes 3D
Bottom Ropes 3D
Border Ropes 2D
Retain Ropes 2D
HE220B
Tie
Shoulder Beam
Single Ropes D22
copy of HE220B
Net Ring Sections
Shell 3t
Shell 4
Shell 3b
Shell 4 edg
Shell 3 edg
Details

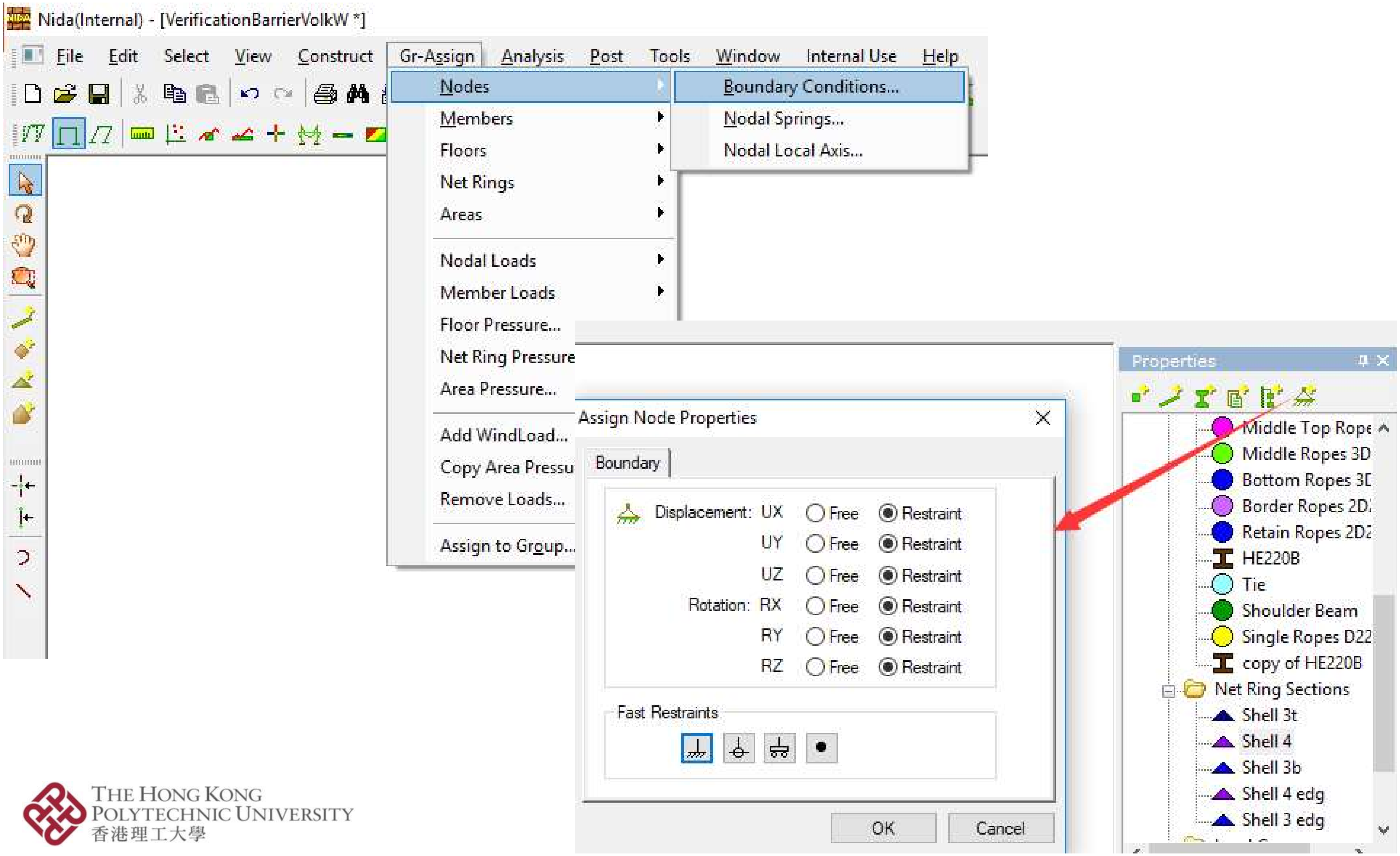
Add Member


File Edit Select View Construct Gr-Assign Analysis Post Tools Window Internal Use Help
New Materials...
New Frame Section
New Net Ring Sections...
New Nodes...
New Members...
New Areas...
New Load Cases...
New Combined Load Cases...
Combined Members... F7
Diaphragms...
Response Spectrum Functions...
Time History Functions...
Semi-Rigid/Spring Models...
Nodal Local Axis...
Groups...
New Member
General
No. : 77
Section : Wingle Ropes 2D22
Length : 0.000
Weight : 0.000
Orientation Angle (Local Axis)
In Degrees 0
K-Node -1
Node 1
Node 2
No. : 0
X : 0
Y : 0
Z : 0
OK
Cancel
Nida(Internal) - [VerificationBarrierVolkW *]
File Edit Select View Construct Gr-Assign Analysis
Member Properties
Section: Wingle Ropes 2D22
End Condition: Both Rigid

Add Net Ring

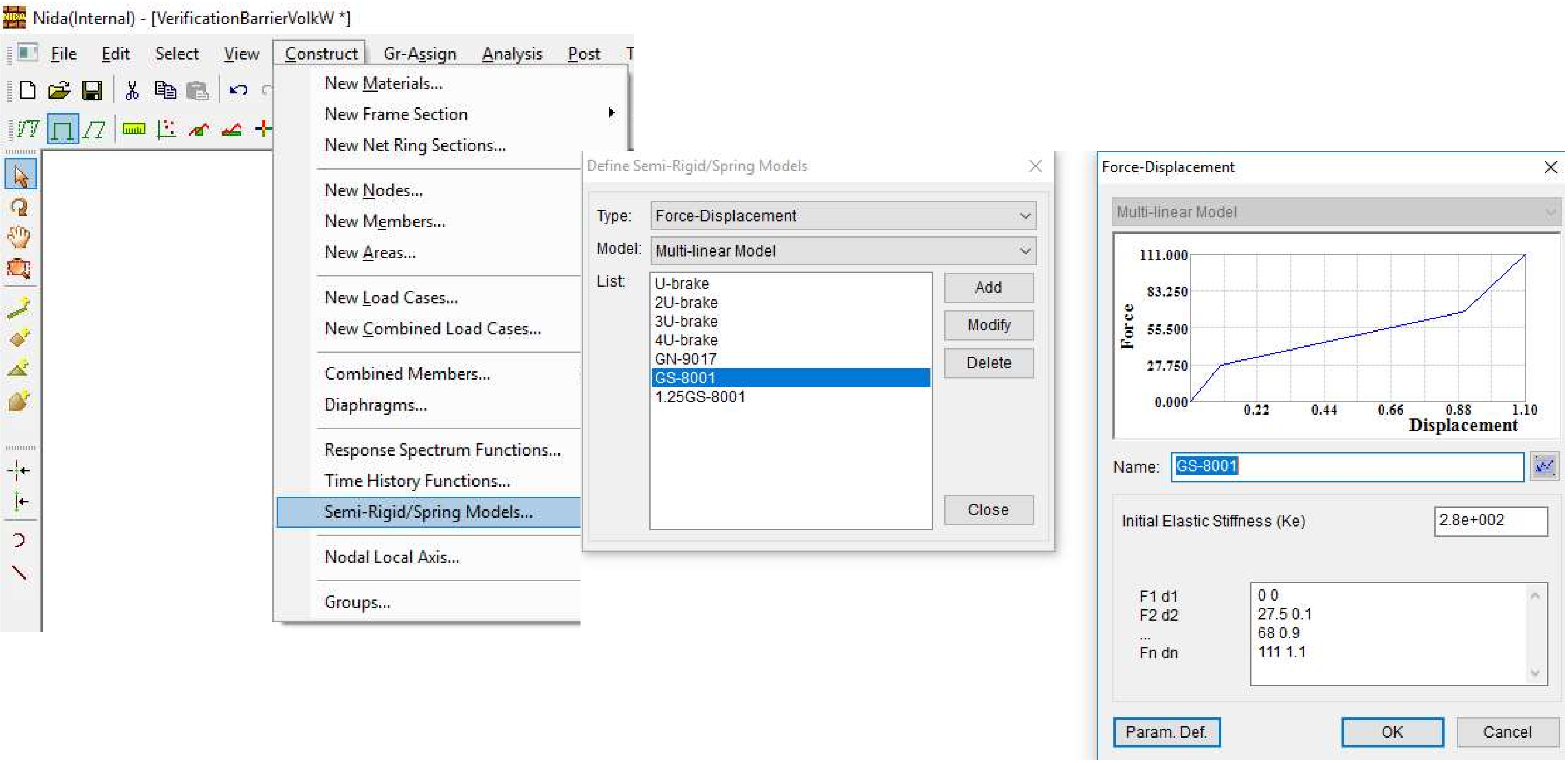

Nida(Internal) - [VerificationBarrierVolkW *]
File
Edit
Select
View
Construct
Gr-Assign
Analysis
Post
3D
Net Ring Property
Section:
Shell 4

Add Boundary Condition

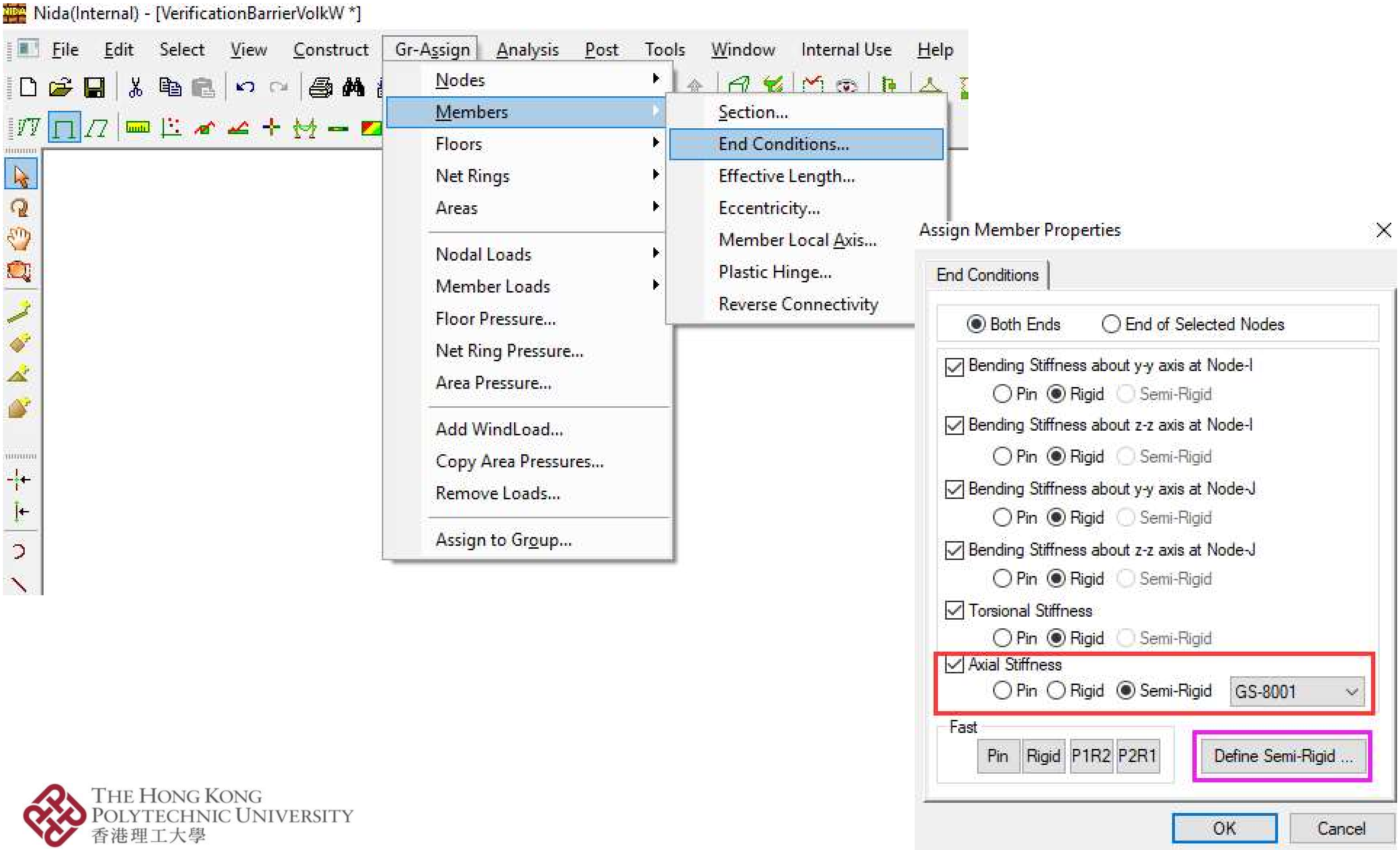


Some Specific Definitions

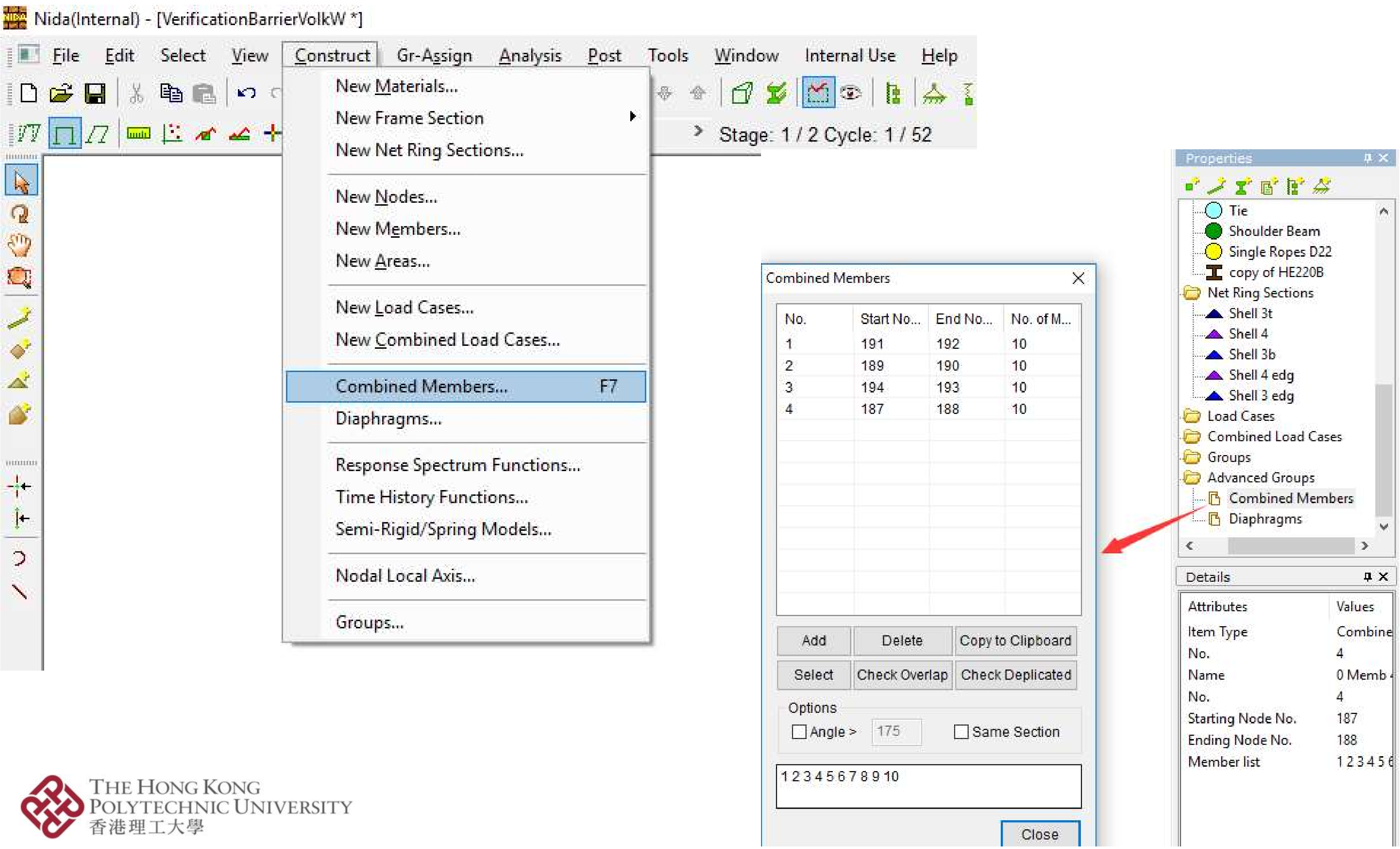
Define Brake Element



Add Brake Element

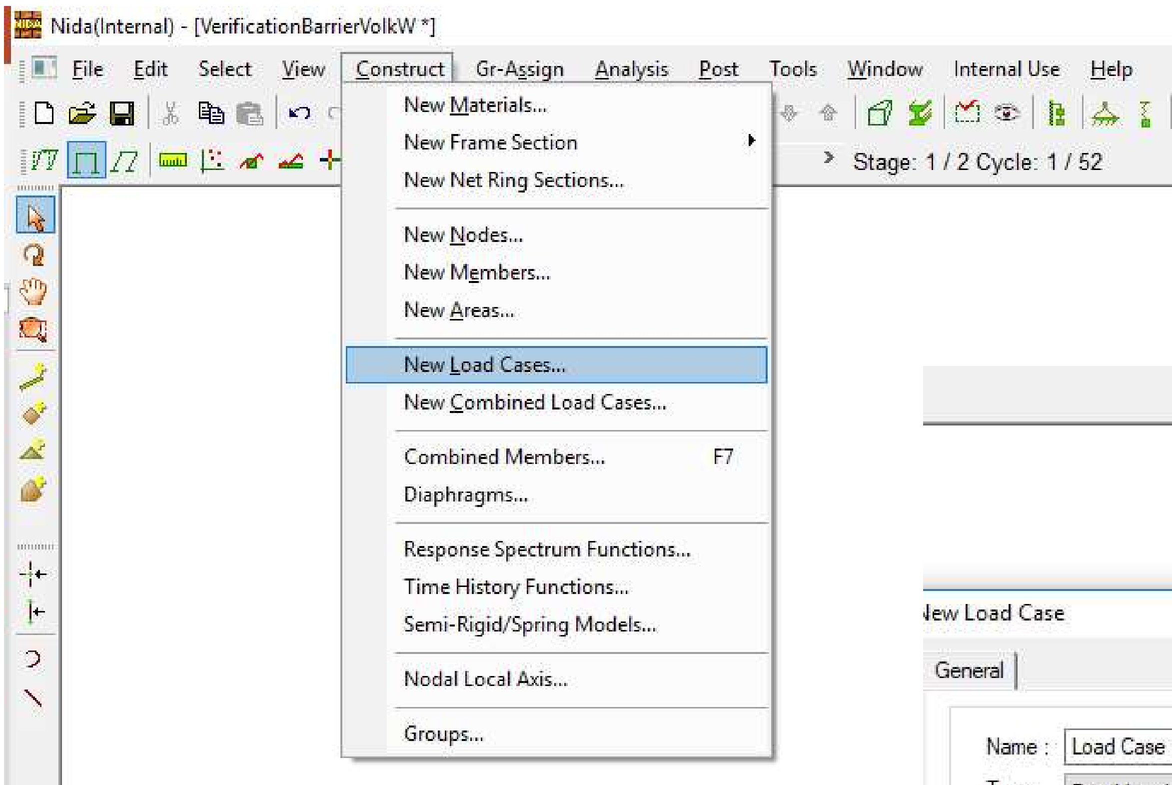


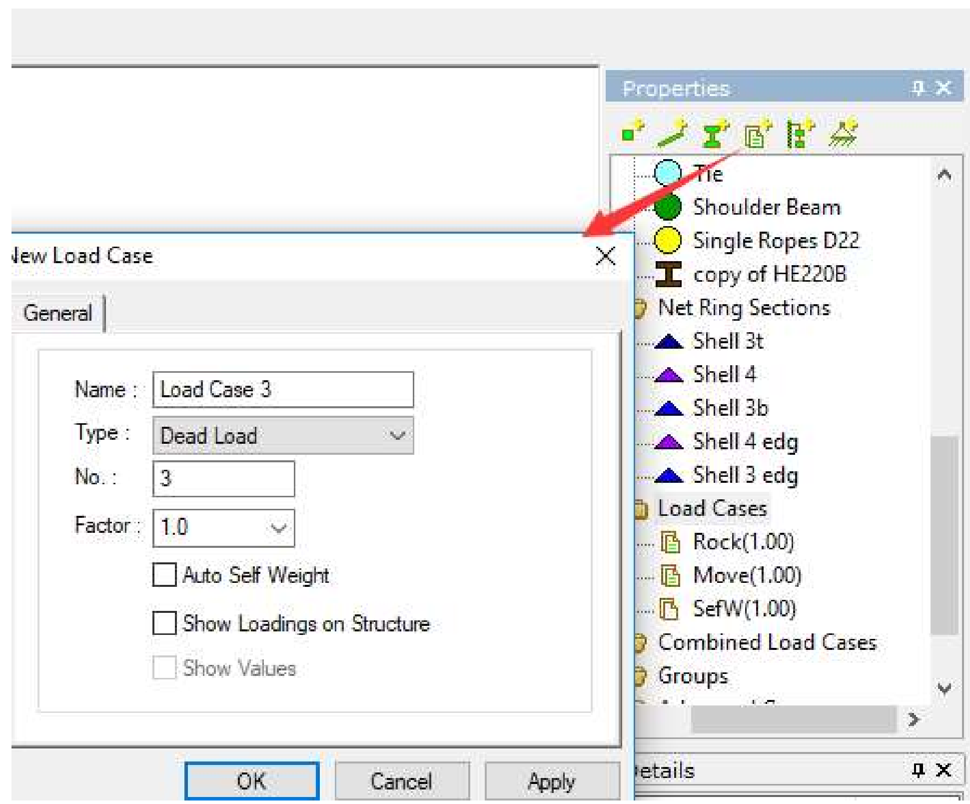
Add Sliding Property Between Shackles and Rope



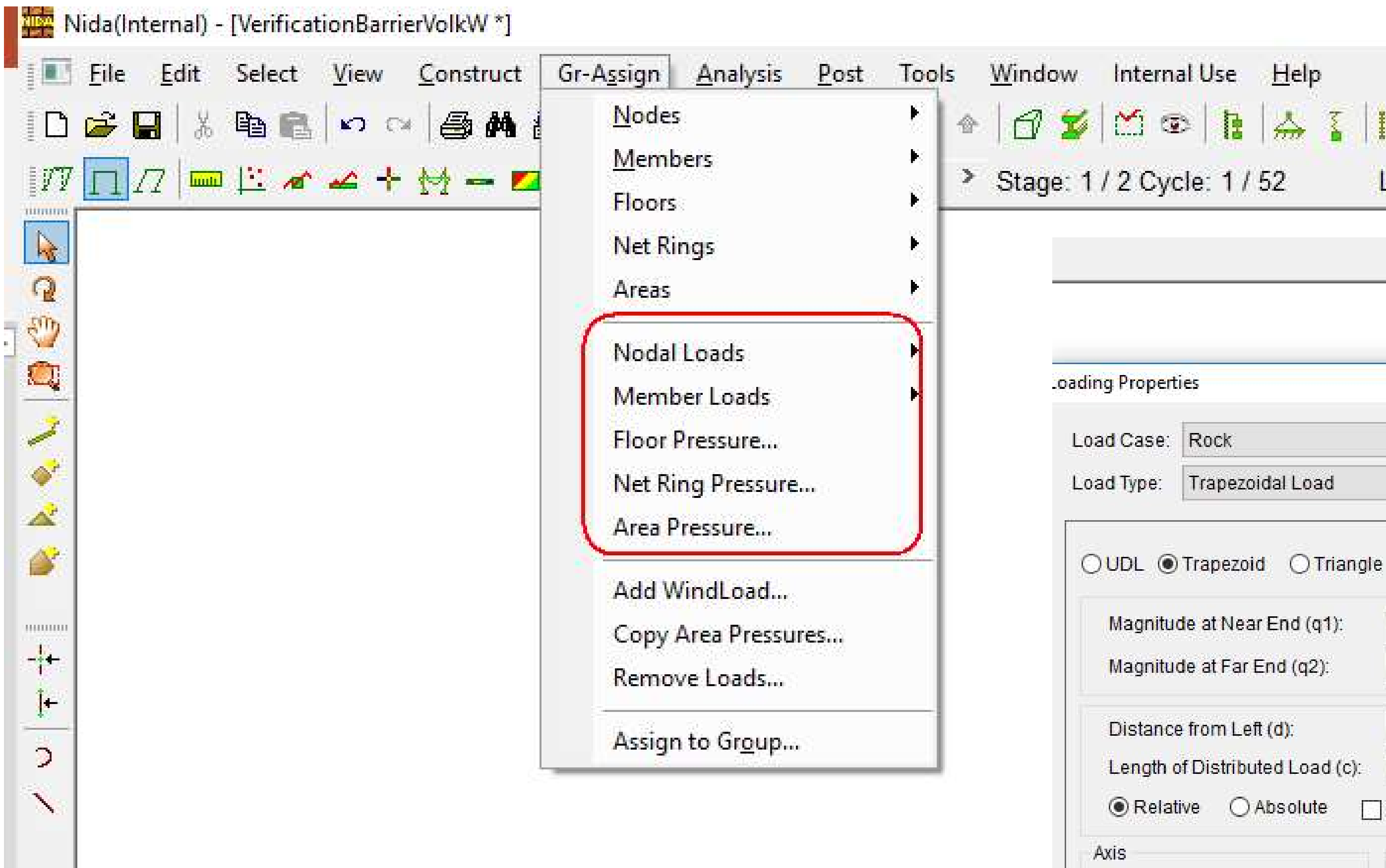
Add Load

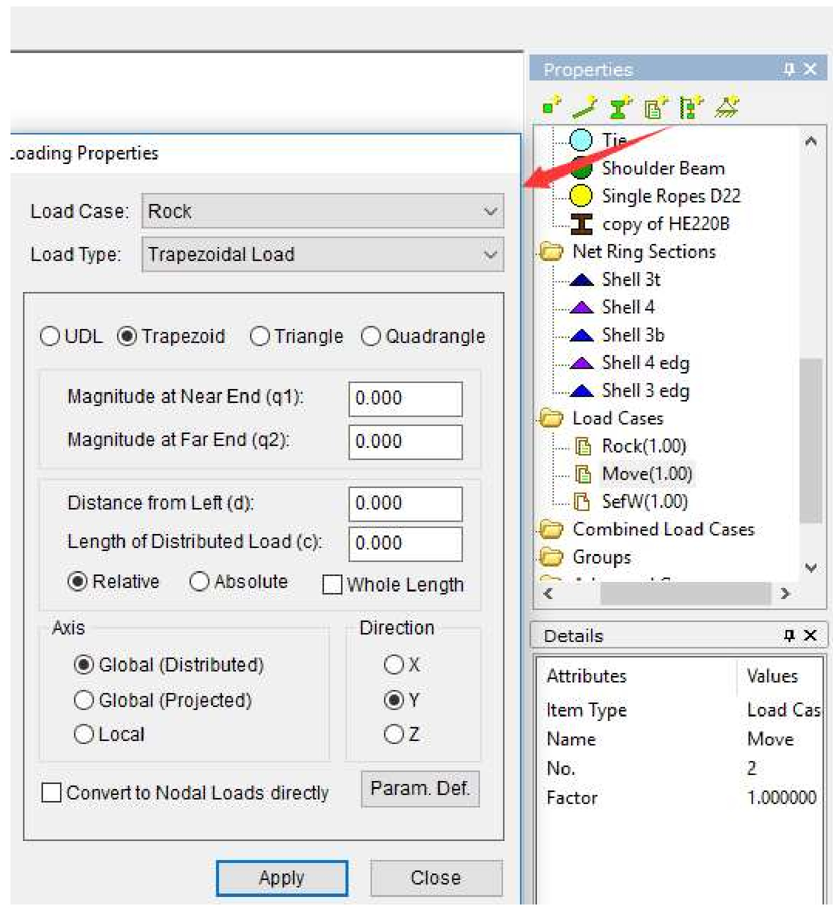
Add Load Case

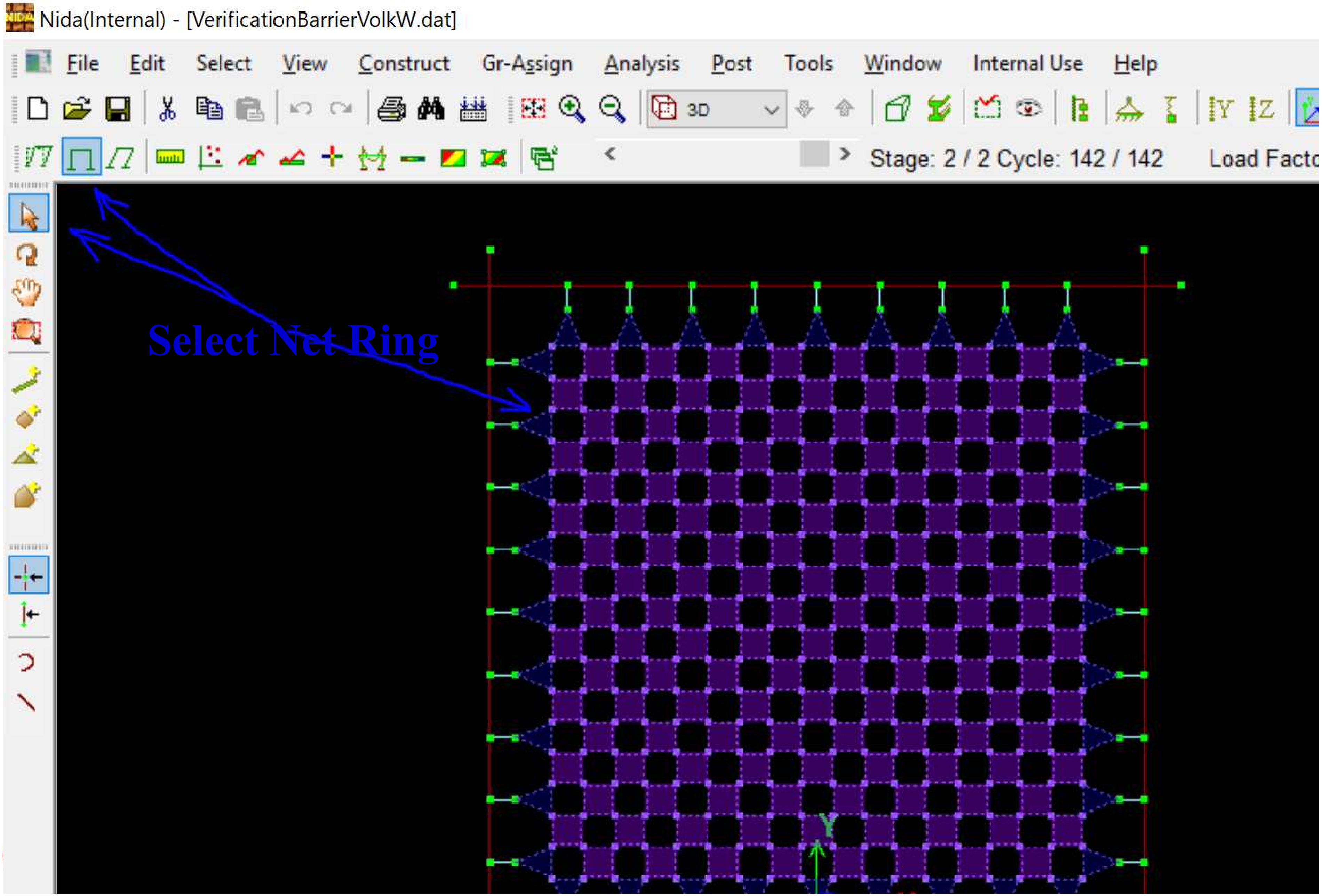


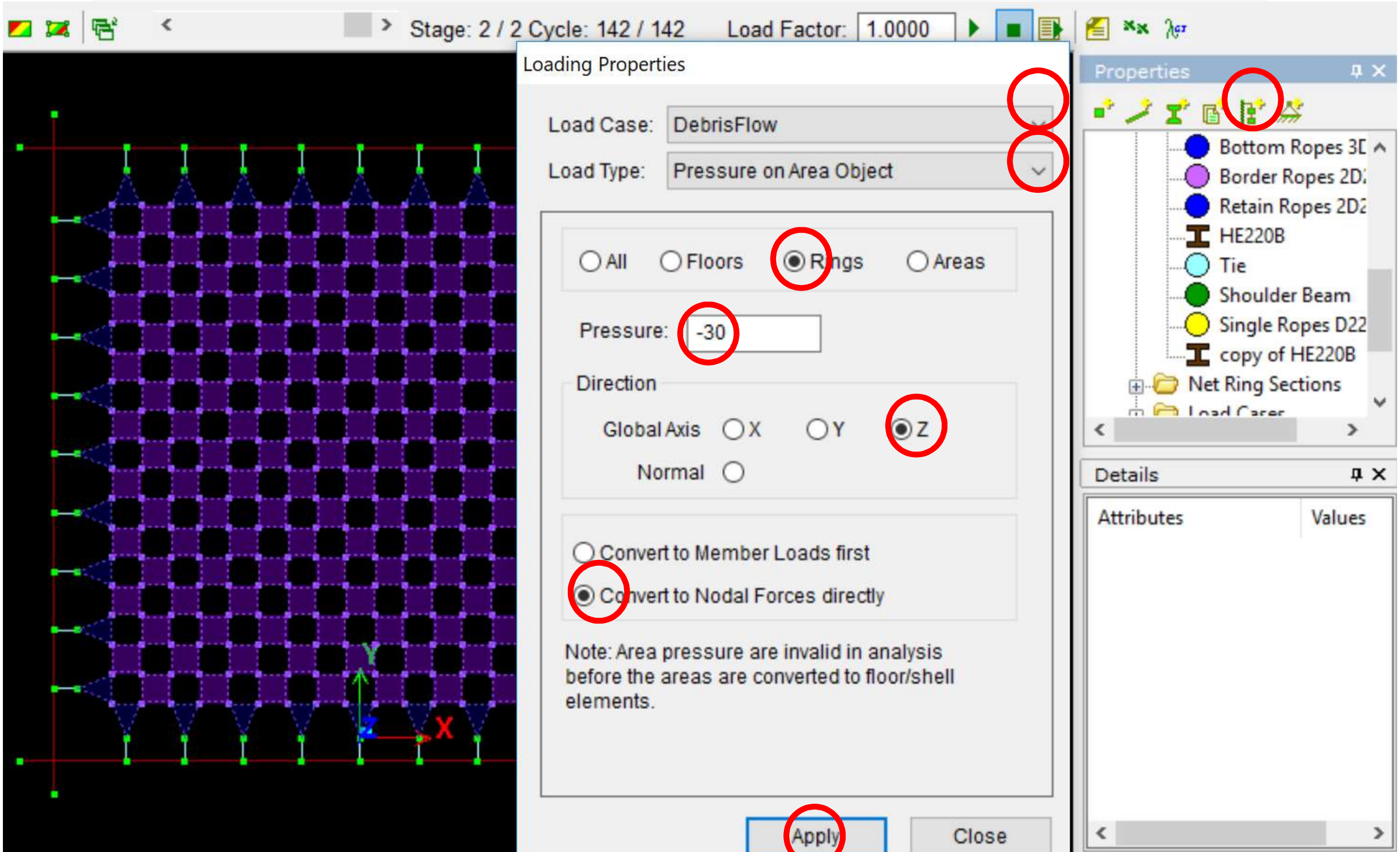


Add Load

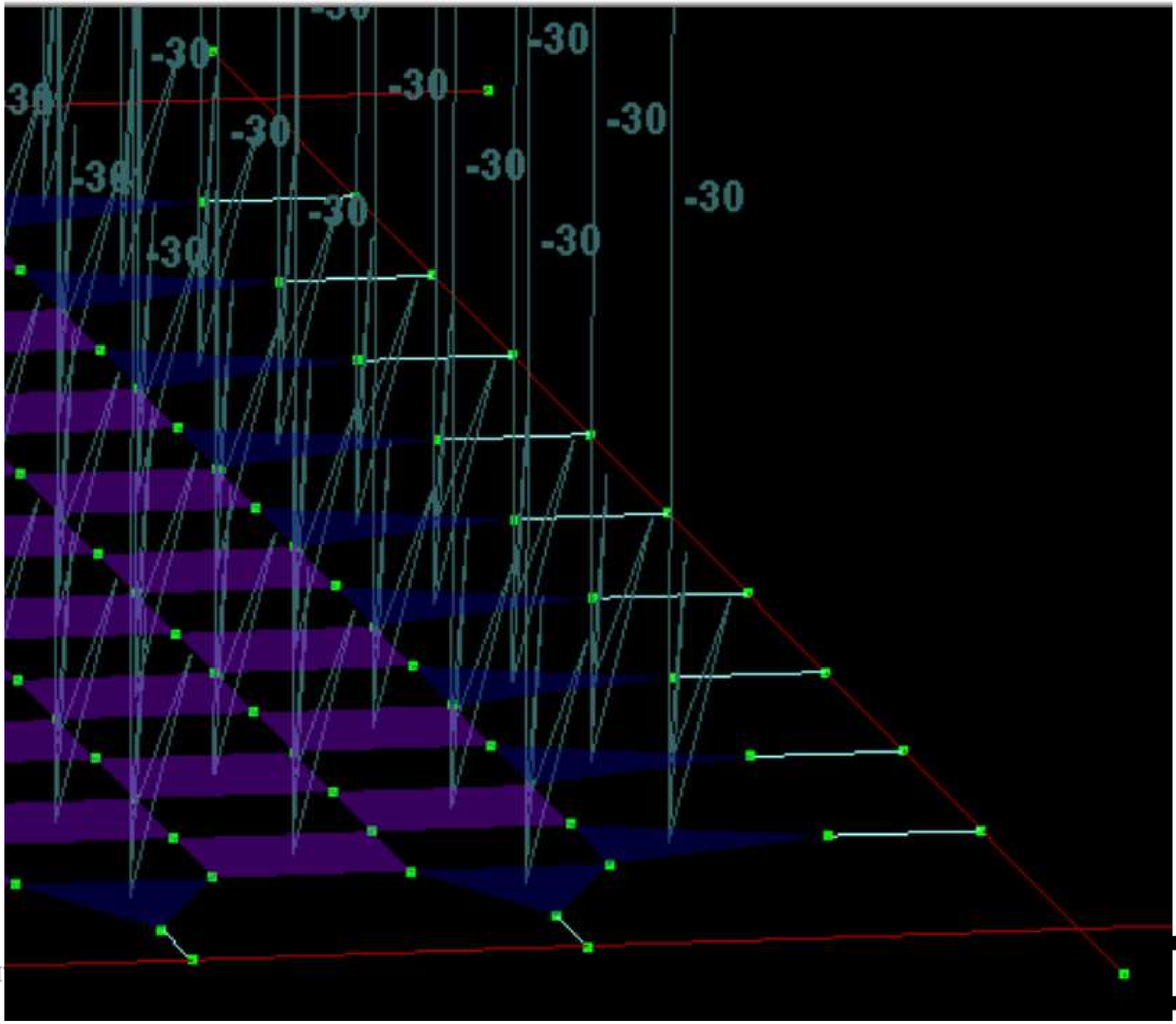

Nida(Internal) - [VerificationBarrierVolkW *]
File
Edit
Select
View
Construct
Gr-Assign
Analysis
Post
Tools
Window
Internal Use
Help
Stage: 1 / 2 Cycle: 1 / 52
Nodes
Members
Floors
Net Rings
Areas
Nodal Loads
Member Loads
Floor Pressure...
Net Ring Pressure...
Area Pressure...
Add WindLoad...
Copy Area Pressures...
Remove Loads...
Assign to Group...


Loading Properties
Load Case:
Rock
Load Type:
Trapezoidal Load
UDL
Trapezoid
Triangle
Quadrangle
Magnitude at Near End (q1):
0.000
Magnitude at Far End (q2):
0.000
Distance from Left (d):
0.000
Length of Distributed Load (c):
0.000
Relative
Absolute
Whole Length
Axis
Global (Distributed)
Global (Projected)
Local
Direction
X
Y
Z
Convert to Nodal Loads directly
Param. Def.
Apply
Close
Properties
Tie
Shoulder Beam
Single Ropes D22
copy of HE220B
Net Ring Sections
Shell 3t
Shell 4
Shell 3b
Shell 4 edg
Shell 3 edg
Load Cases
Rock(1.00)
Move(1.00)
SefW(1.00)
Combined Load Cases
Groups
Details
Attributes
Values
Item Type
Load Cas
Name
Move
No.
2
Factor
1.000000

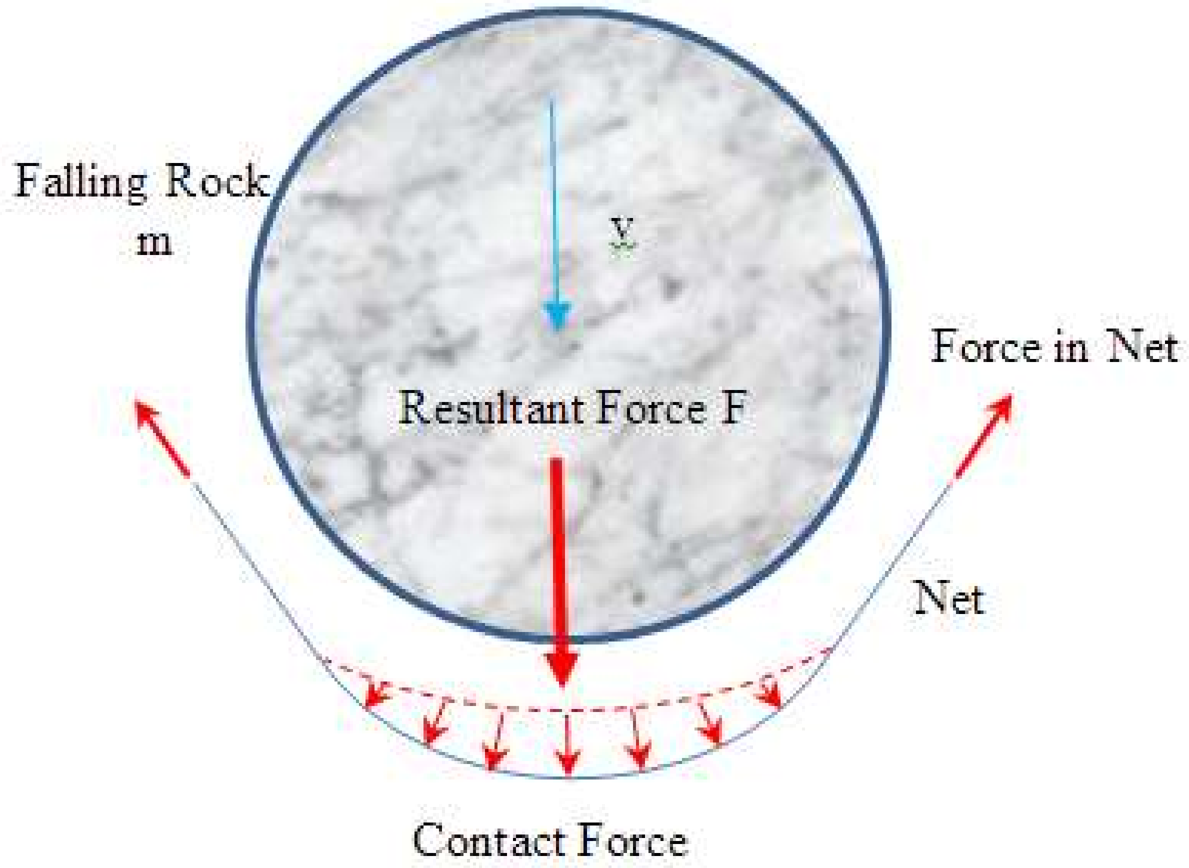

Nida(Internal) - [VerificationBarrierVolkW.dat]
File Edit Select View Construct Gr-Assign Analysis Post Tools Window Internal Use Help
3D
Stage: 2 / 2 Cycle: 142 / 142
Load Facto
Select Net Ring
Y


Stage: 2 / 2 Cycle: 142 / 142
Load Factor: 1.0000
Loading Properties
Load Case: DebrisFlow
Load Type: Pressure on Area Object
All
Floors
Rings
Areas
Pressure: -30
Direction
Global Axis X Y Z
Normal
Convert to Member Loads first
Convert to Nodal Forces directly
Note: Area pressure are invalid in analysis before the areas are converted to floor/shell elements.
Apply
Close
Properties
Bottom Ropes 3D
Border Ropes 2D
Retain Ropes 2D
HE220B
Tie
Shoulder Beam
Single Ropes D22
copy of HE220B
Net Ring Sections
Details
Attributes
Values

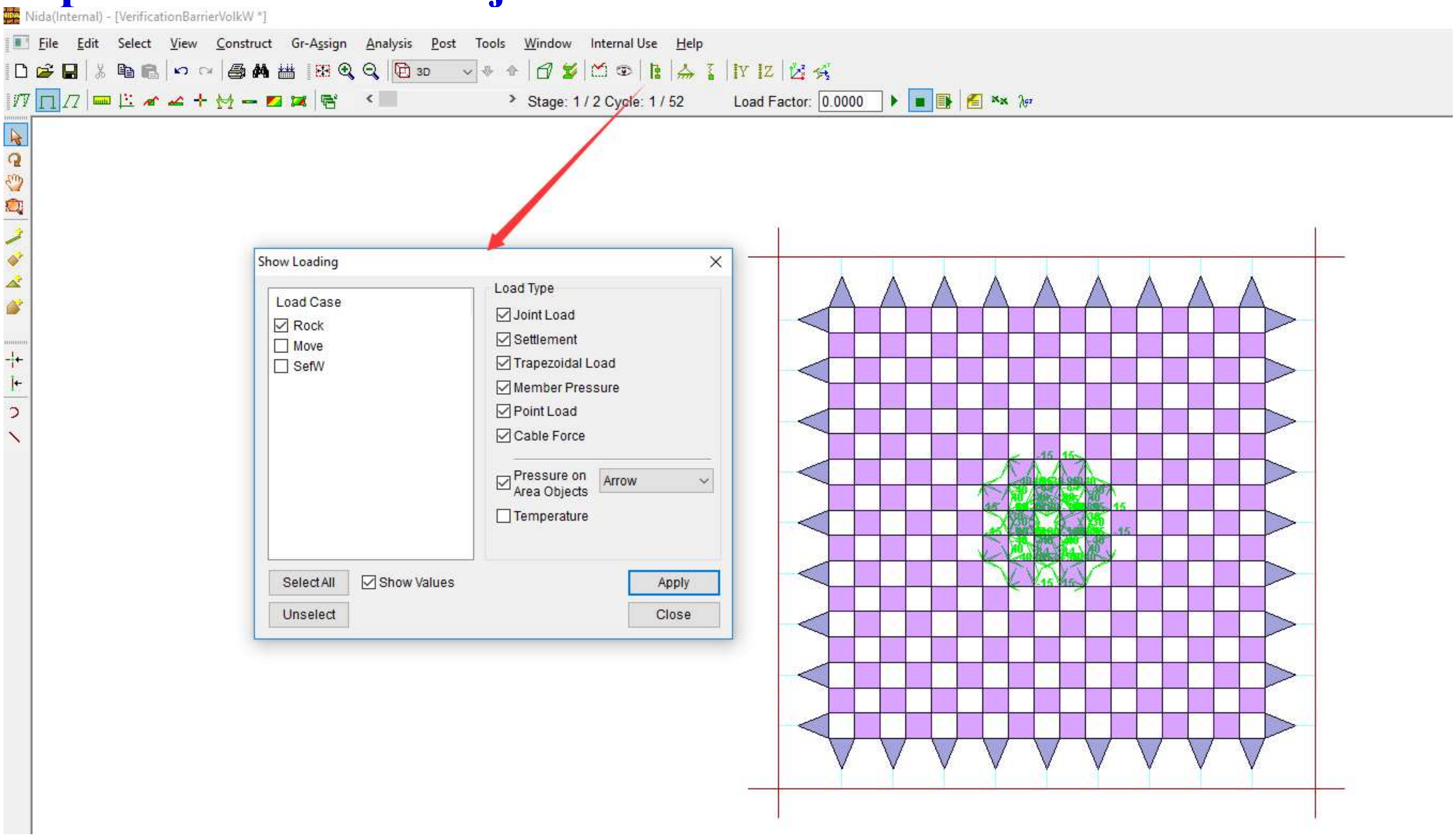
Show Loading



Impact force of rock – joint load

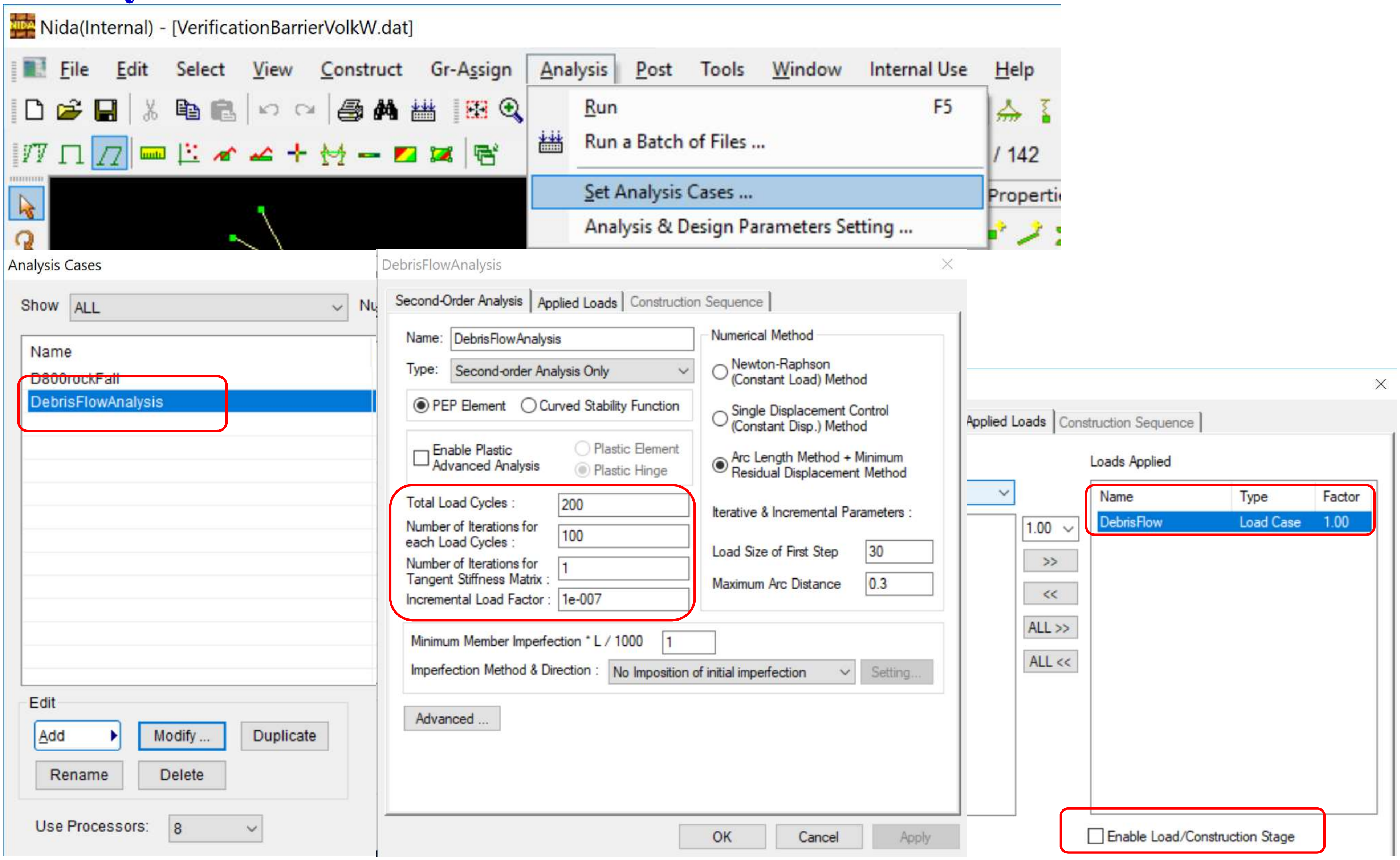


Impact force of rock – joint load

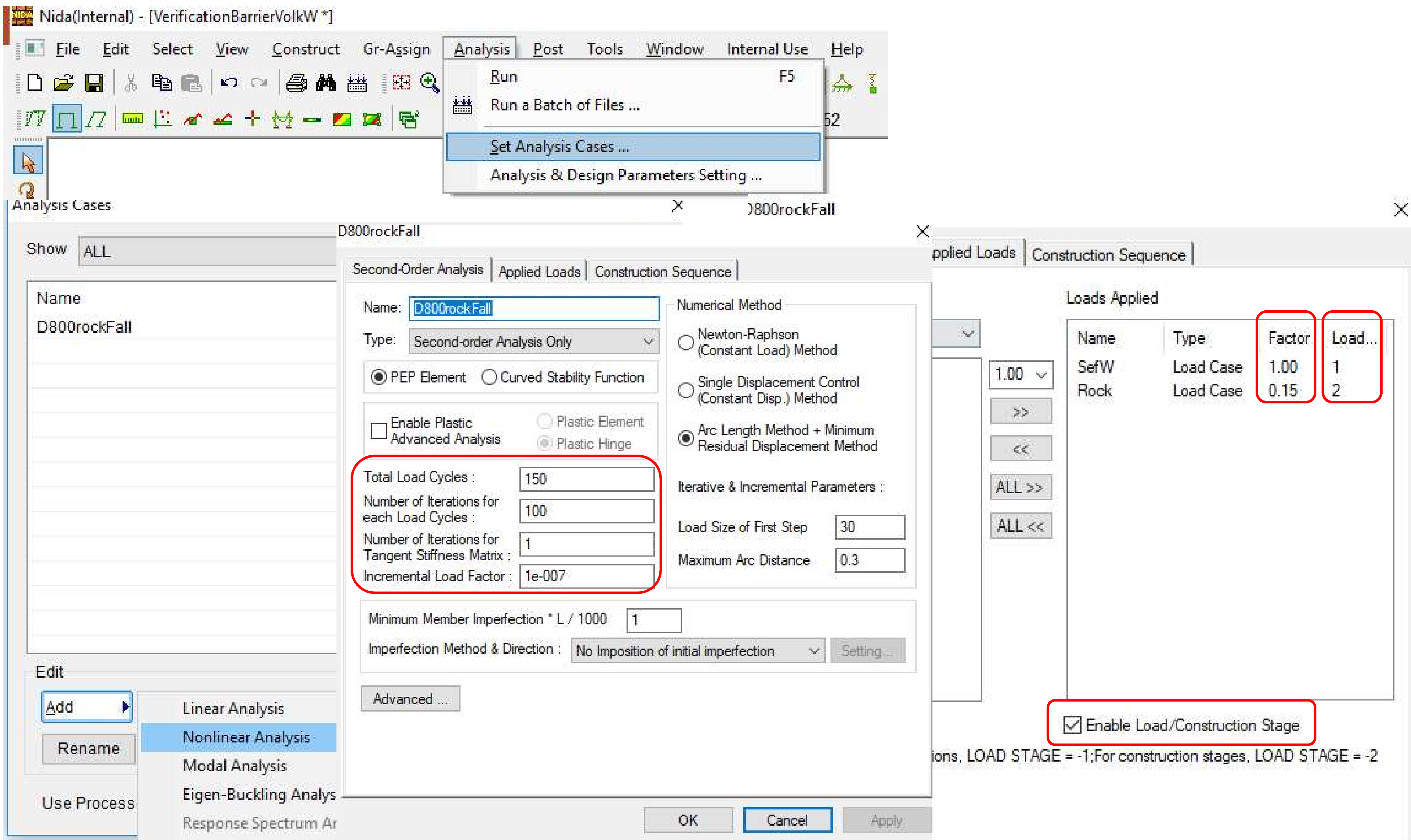


Set Analysis Case

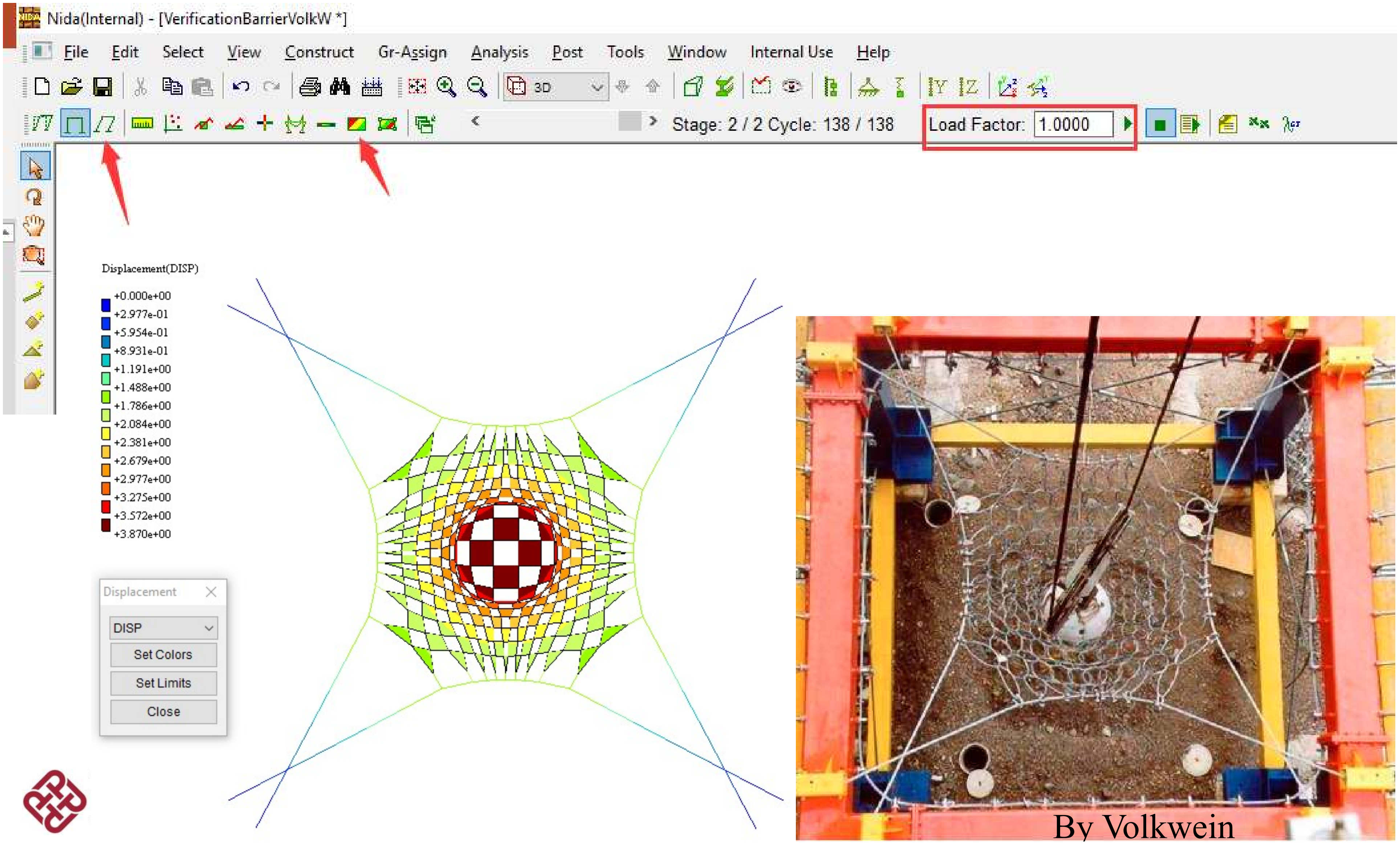
Analysis Case



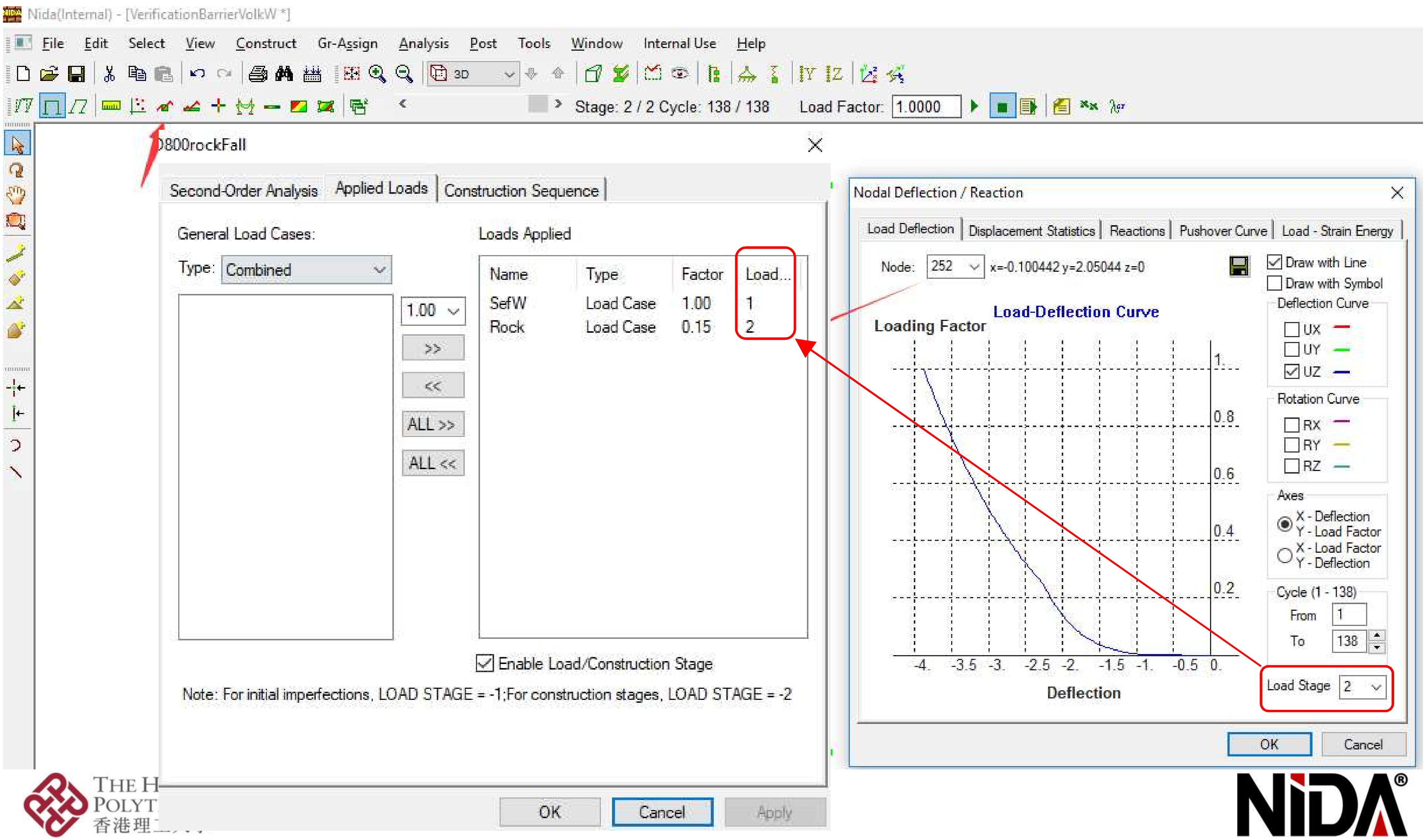
Analysis Case



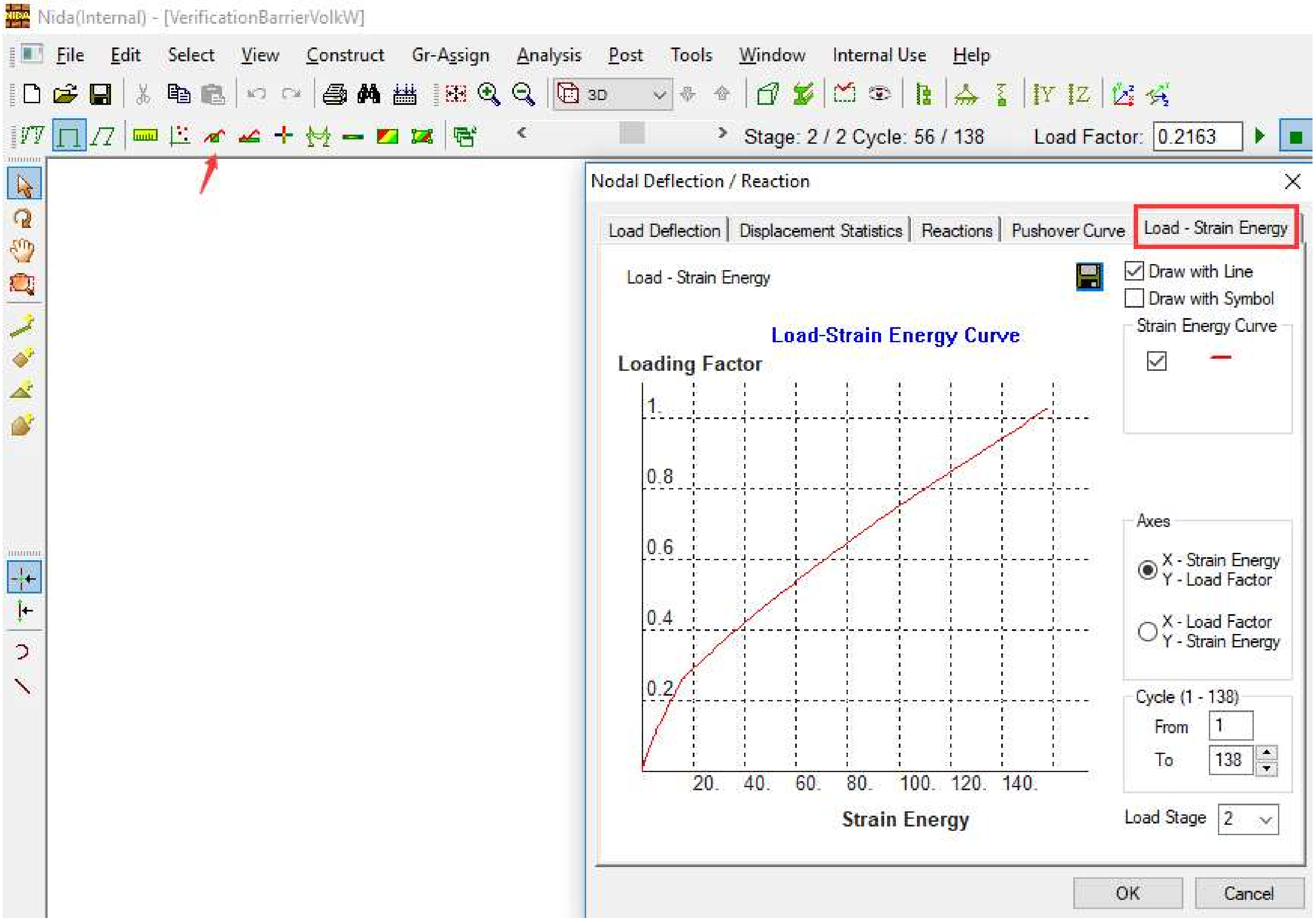
Nodal Displacement Contour



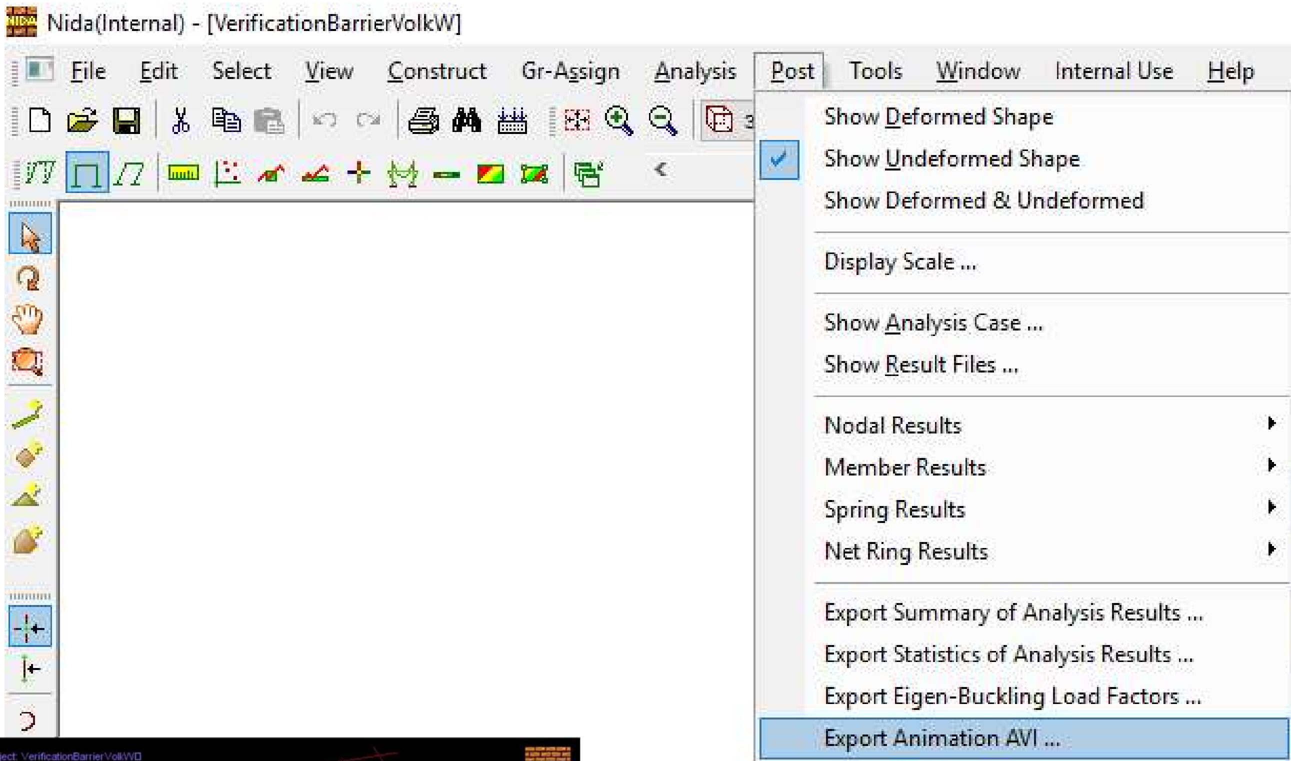
Nodal Deflection

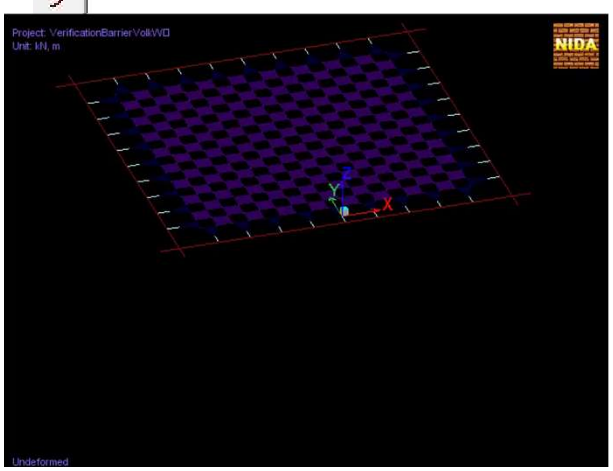


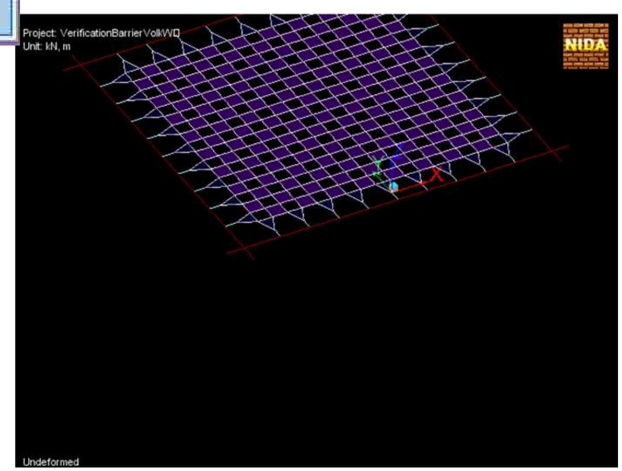
Nodal Deflection



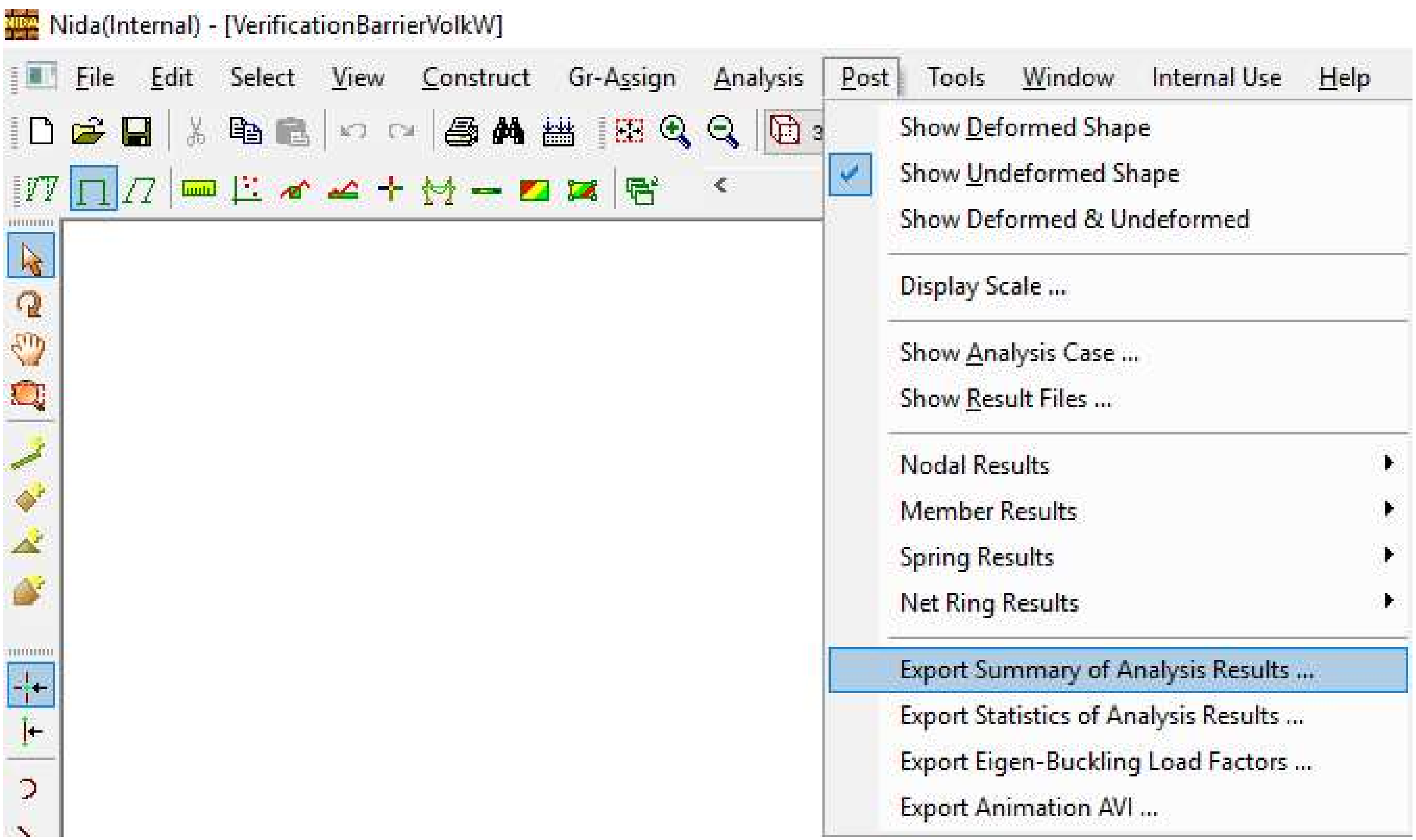
Export Animation AVI







Others: Reaction Forces, Result Data Output



THANK YOU

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Design Experience Sharing of A Selected Project

Ir Dr Raymond Koo & Ir Dr Eric Sze
Geotechnical Engineer

GEOTECHNICAL ENGINEERING OFFICE

Date: 16 April 2019

Outline

1. **Project Background**
2. **Design using Force Approach (NIDA-MNN)**
3. **Design Optimisation using Coupled Analysis (LS-DYNA)**

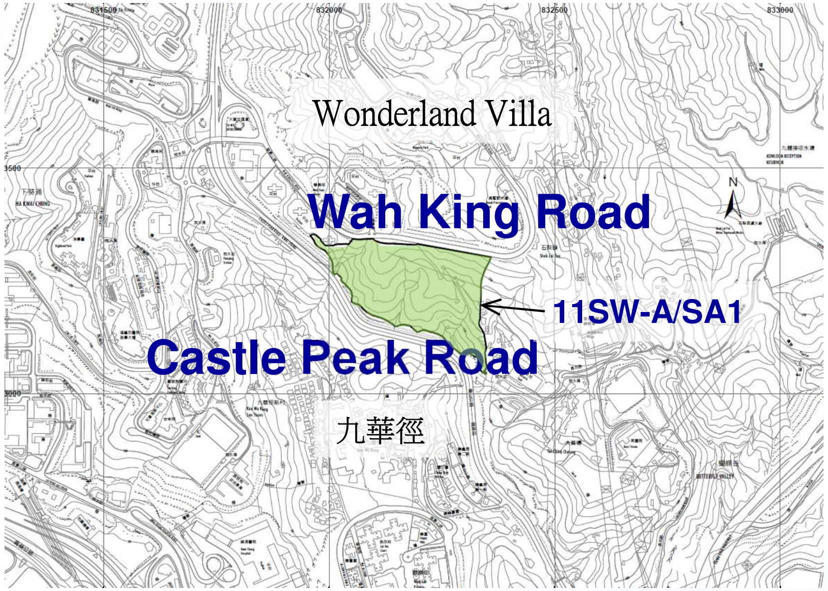
Eric (items 1–2)

Raymond (item 3)

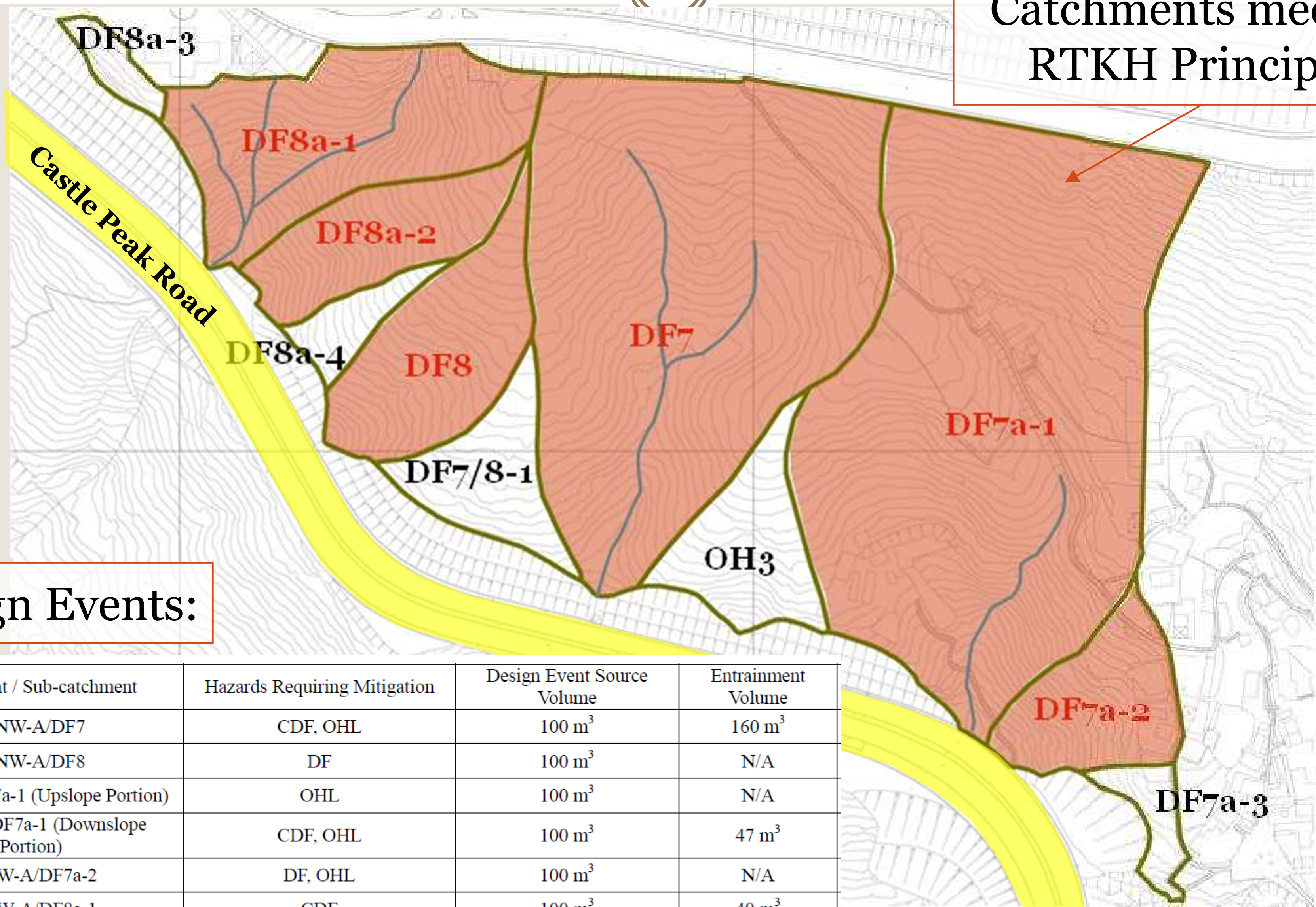
1. Project Background

In-house LPMit Project

Site constraints:
- Squatter, Private Lot, Existing Soil Nails



Key Findings of NTHS

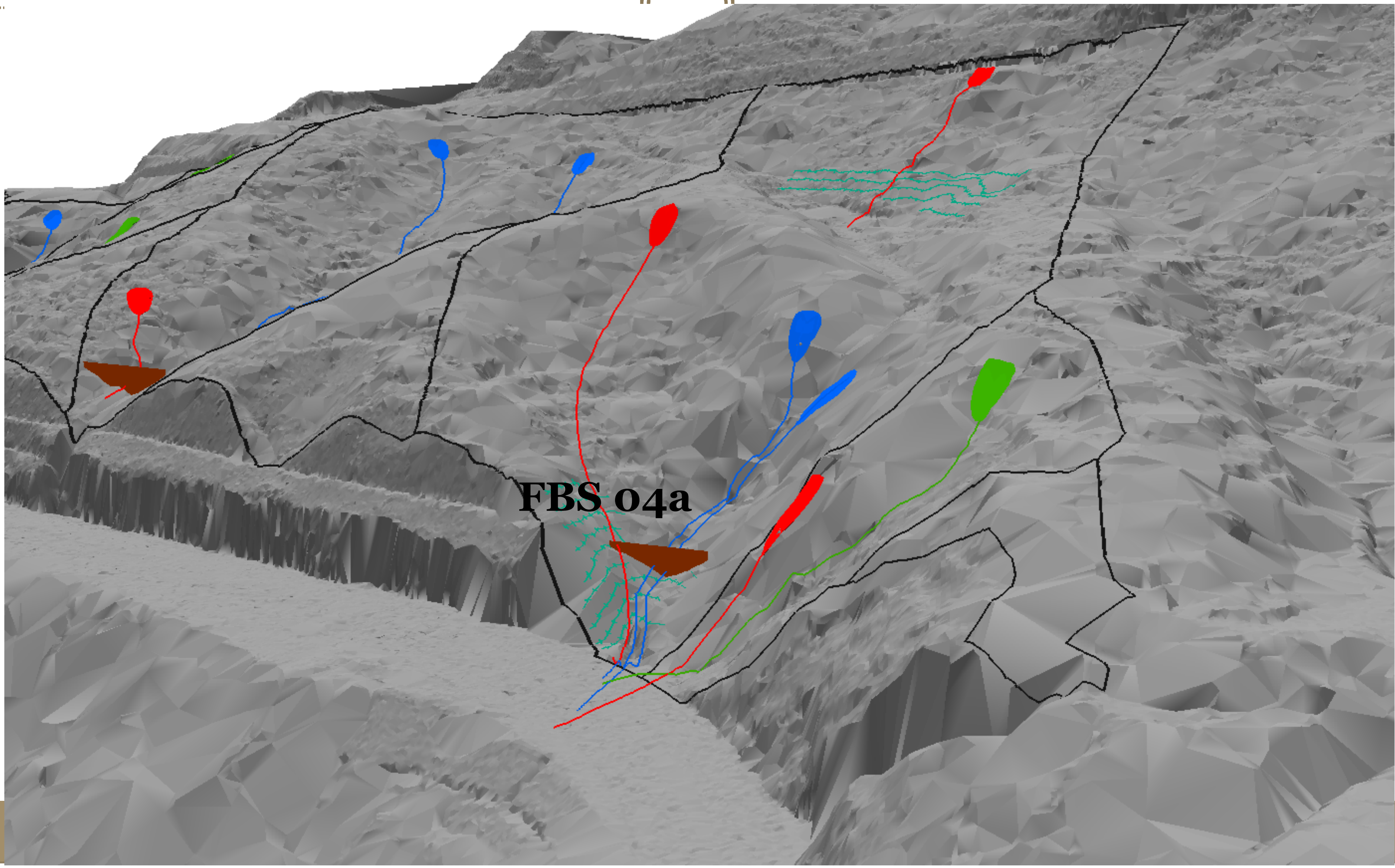


Catchments meeting RTKH Principles

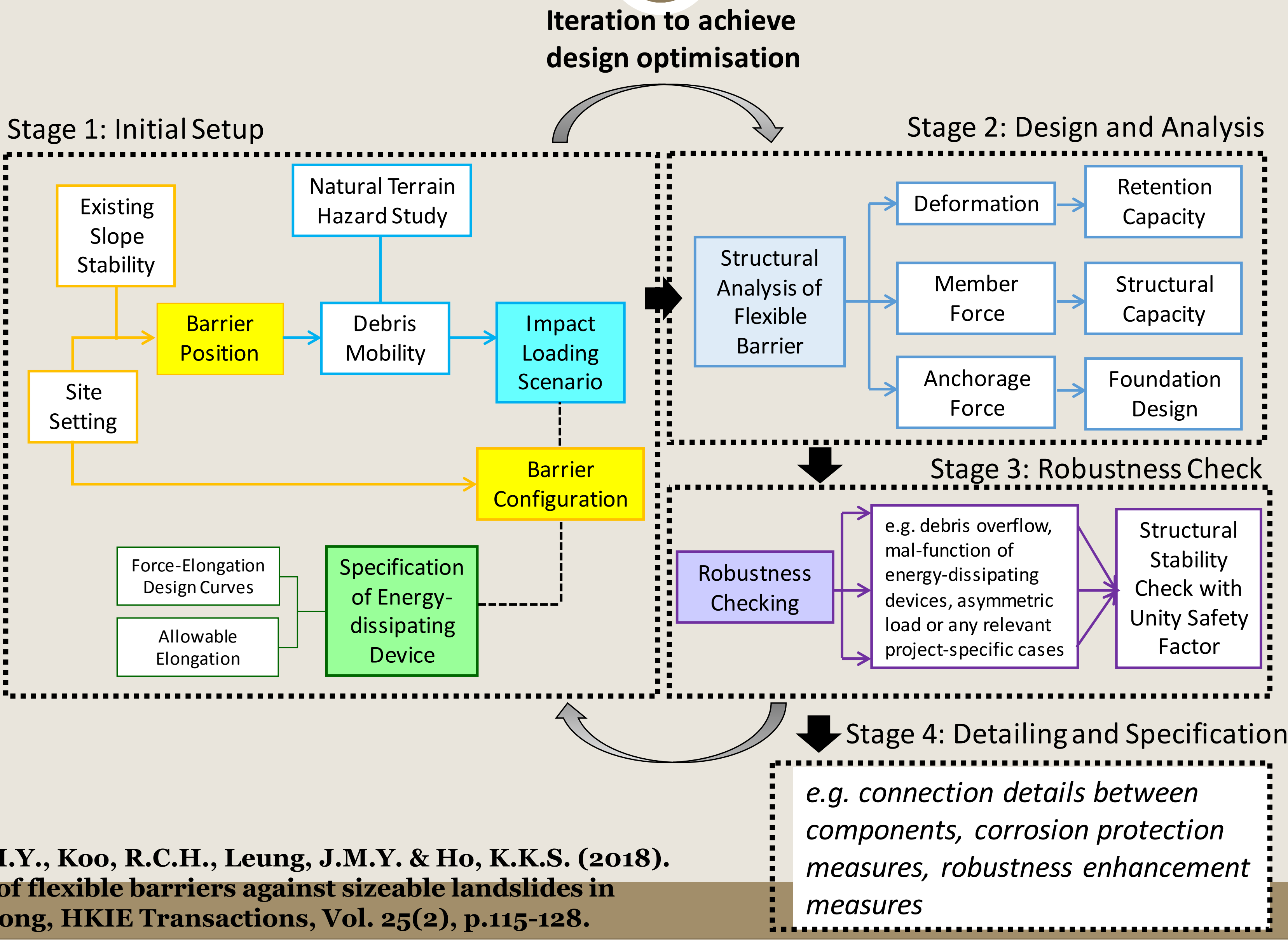
Design Events:

Catchment / Sub-catchment	Hazards Requiring Mitigation	Design Event Source Volume	Entrainment Volume
11NW-A/DF7	CDF, OHL	100 m^3	160 m^3
11NW-A/DF8	DF	100 m^3	N/A
11NW-A/DF7a-1 (Upslope Portion)	OHL	100 m^3	N/A
11NW-A/DF7a-1 (Downslope Portion)	CDF, OHL	100 m^3	47 m^3
11NW-A/DF7a-2	DF, OHL	100 m^3	N/A
11NW-A/DF8a-1	CDF	100 m^3	40 m^3
11NW-A/DF8a-2	DF	100 m^3	N/A

2. Design Using Force Approach



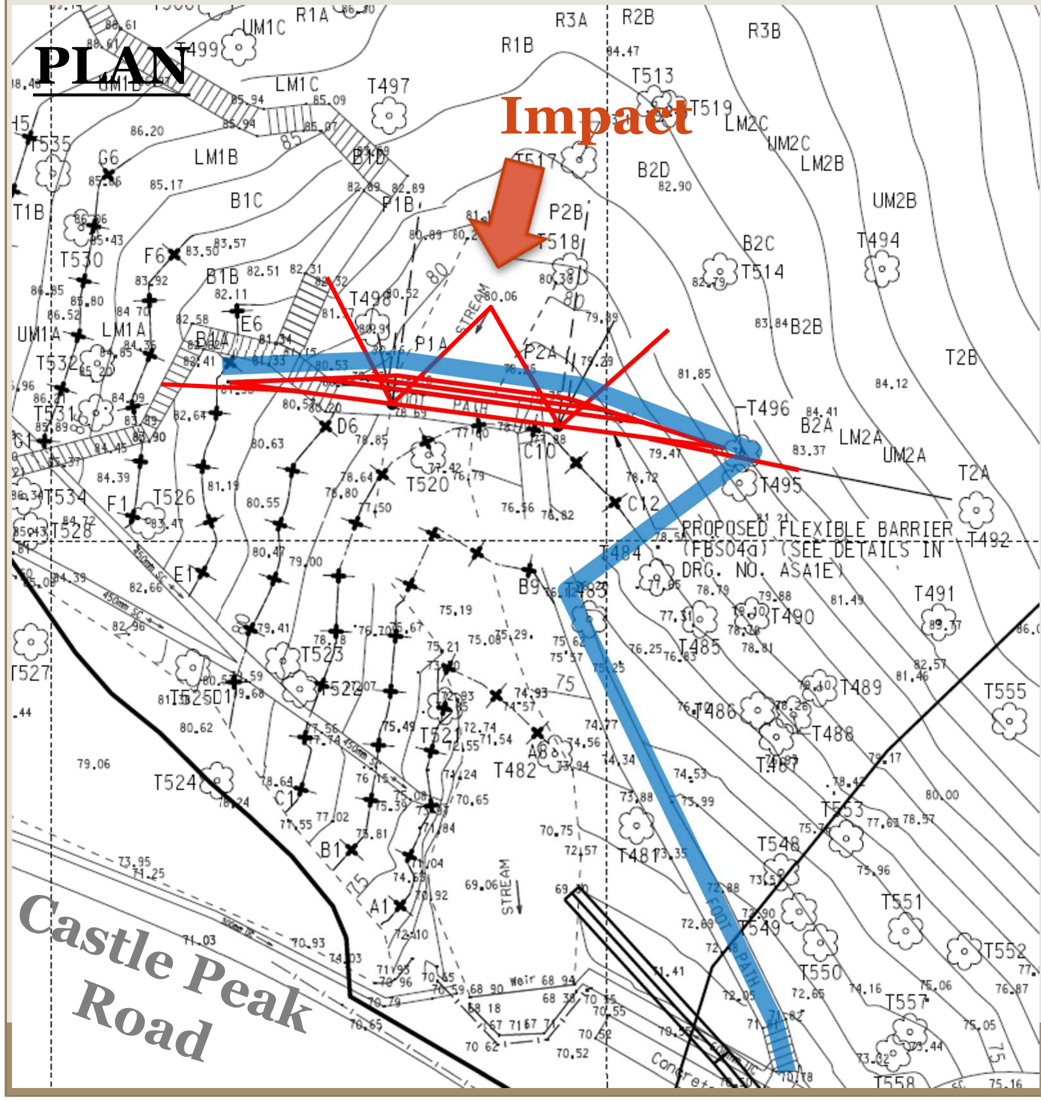
General Design Procedures

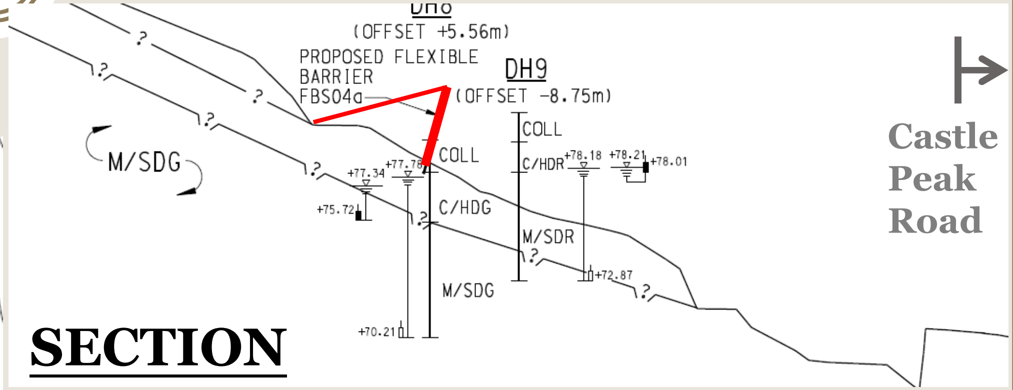


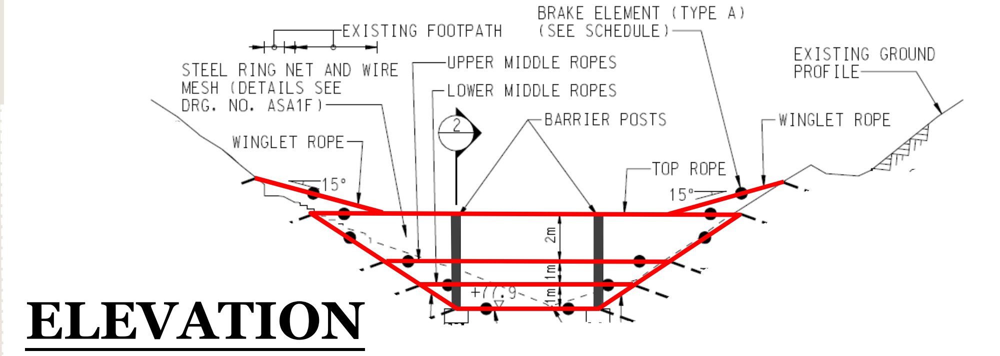
Sze, E.H.Y., Koo, R.C.H., Leung, J.M.Y. & Ho, K.K.S. (2018). Design of flexible barriers against sizeable landslides in Hong Kong, HKIE Transactions, Vol. 25(2), p.115-128.

Site Setting

- FBS04a

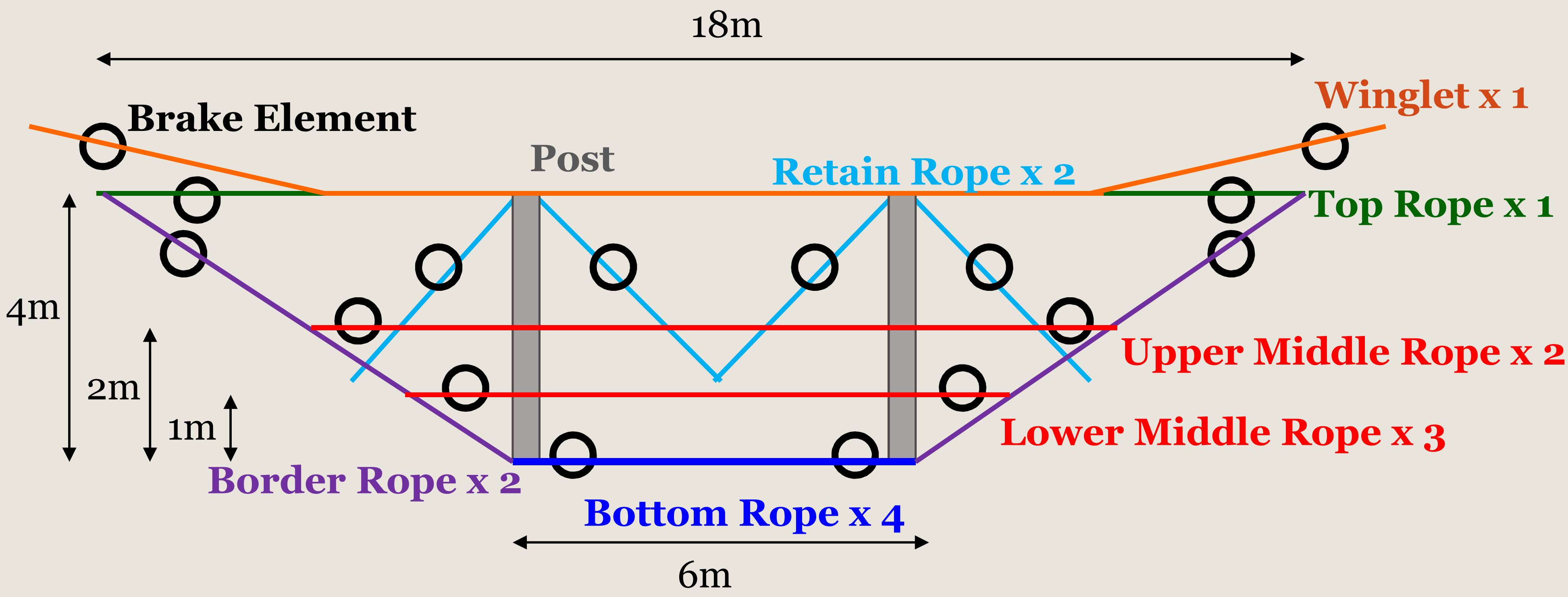




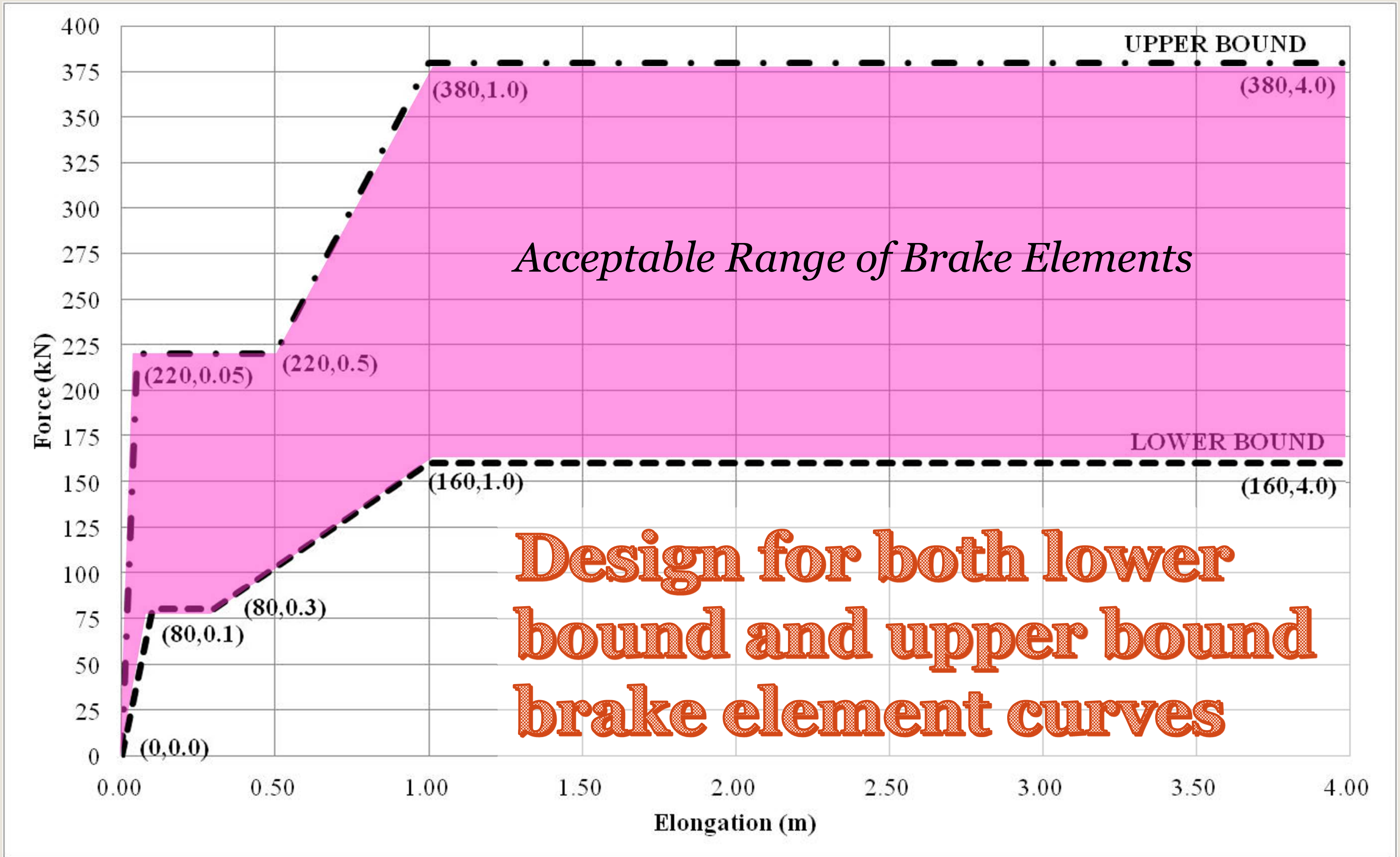


Barrier Layout

- Rope, Ring Net, Brake Element Arrangement



Design Force-Elongation Curve for Brake Elements



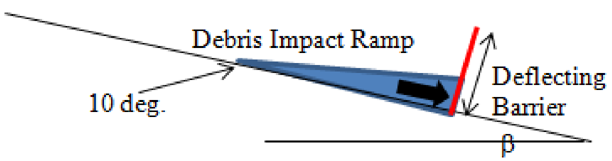
Design for both lower bound and upper bound brake element curves

Impact Volume and Retention Capacity

Definition of Debris Impact Ramp (Each Phase)

According to DN1/2012,

Taking debris ramp impact at 10 deg.



Calculation of Design Debris Impact Height and No. of Impact Phases

Total Debris Impact Volume = 138.9 m^3

According to Table below,

Total Ramp Volume = 197.3 m^3

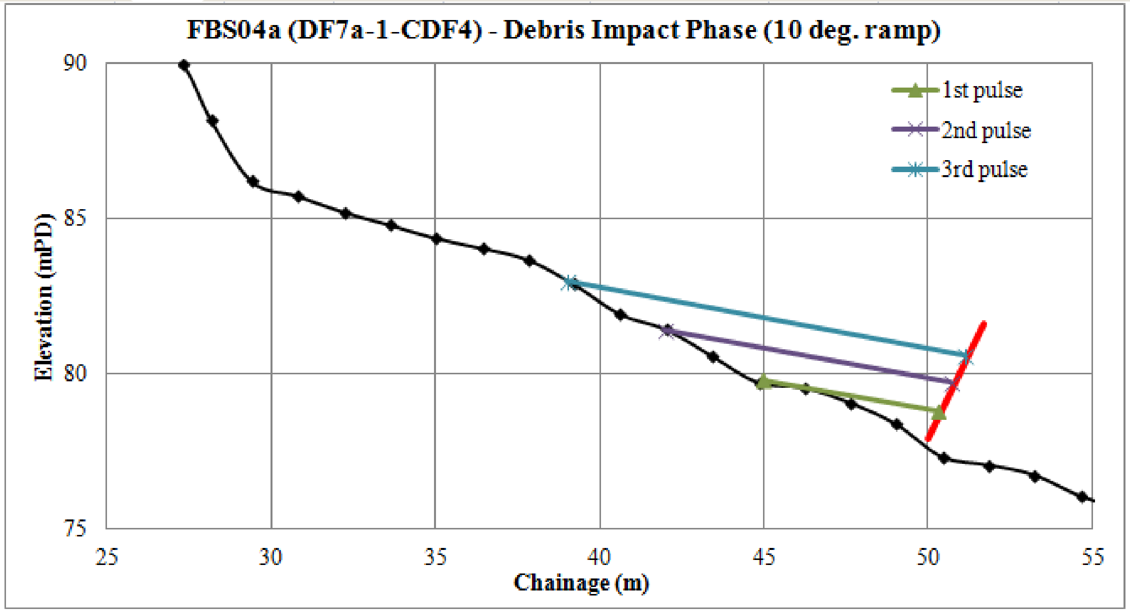
under Impact Phase No. 3

Therefore,

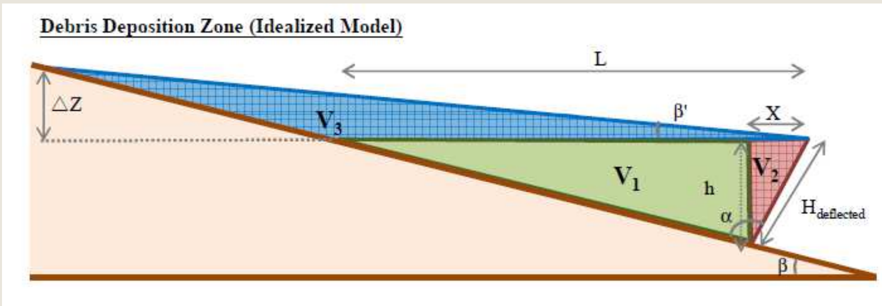
No. of Design Impact Phases = **3**

Height of Design Impact Phases = **3.0** m

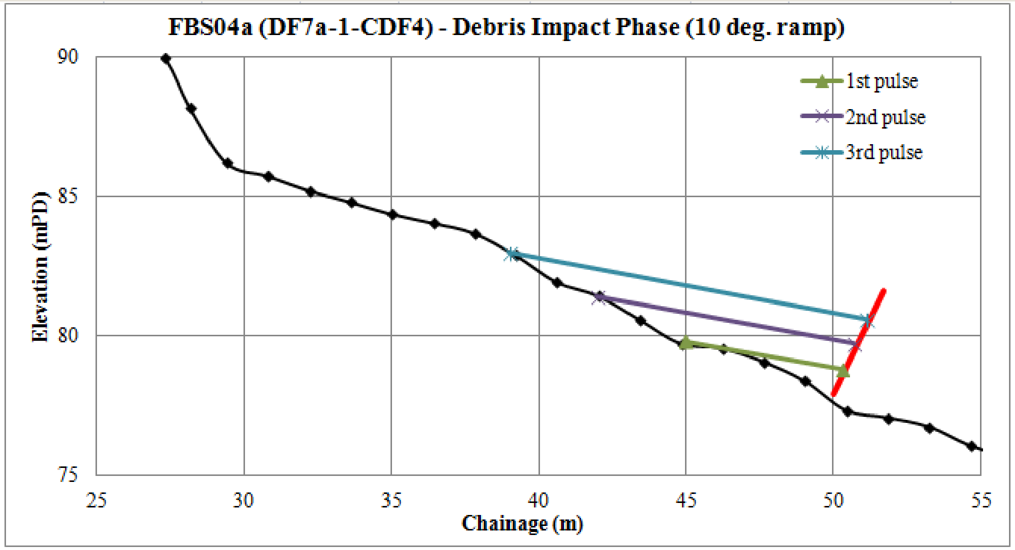
8% Bulking Factor (GEO Report 104)



- Later modelling found that barrier sags by 1 m, hence the retention capacity of the deflected barrier = **<u>252 m³</u>**
  - Actual topography considered
  - Barrier dimensions considered
  - Bulged-out volume ignored

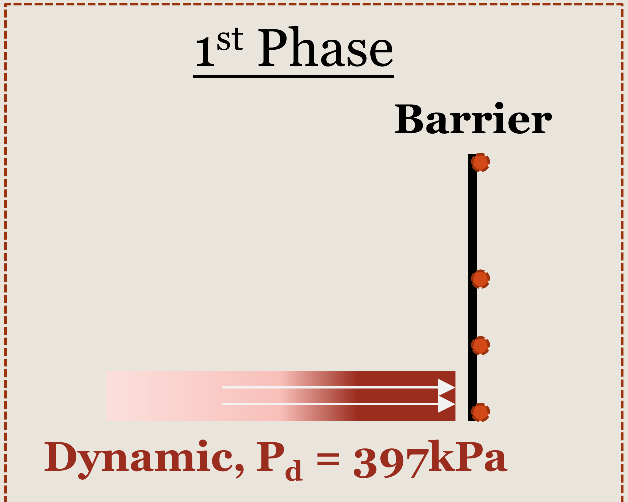


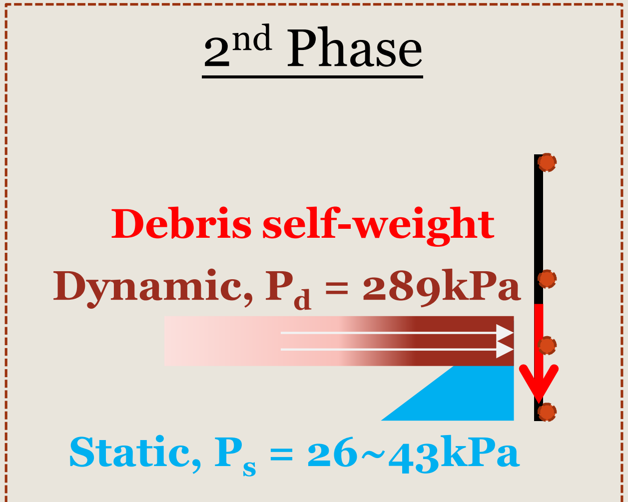
Design Impact Scenario

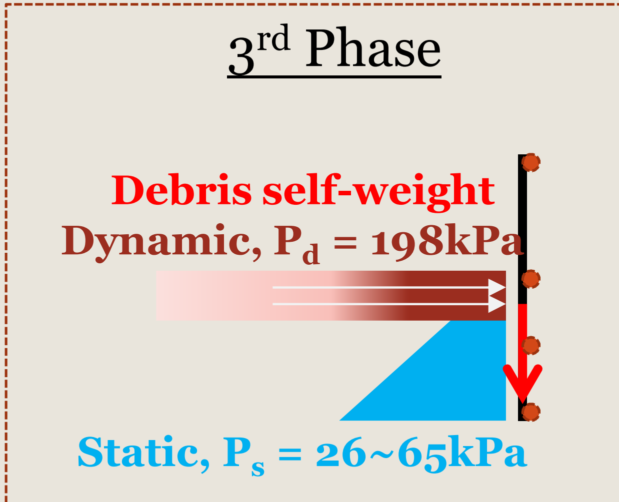


Consideration of impact velocity reduction (TGN44)

No. of Phase	Vol. of Individual Phase (m^3)	Cul. Vol. of Phases (m^3)	Impact Duration (s)	Design Velocity (m/s)	Dynamic Pressure (kPa)
1	24	24	6.77	9.5	**397.1**
2	70	93	8.91	8.1	**288.7**
3	159	253	Completed	6.7	**197.5**



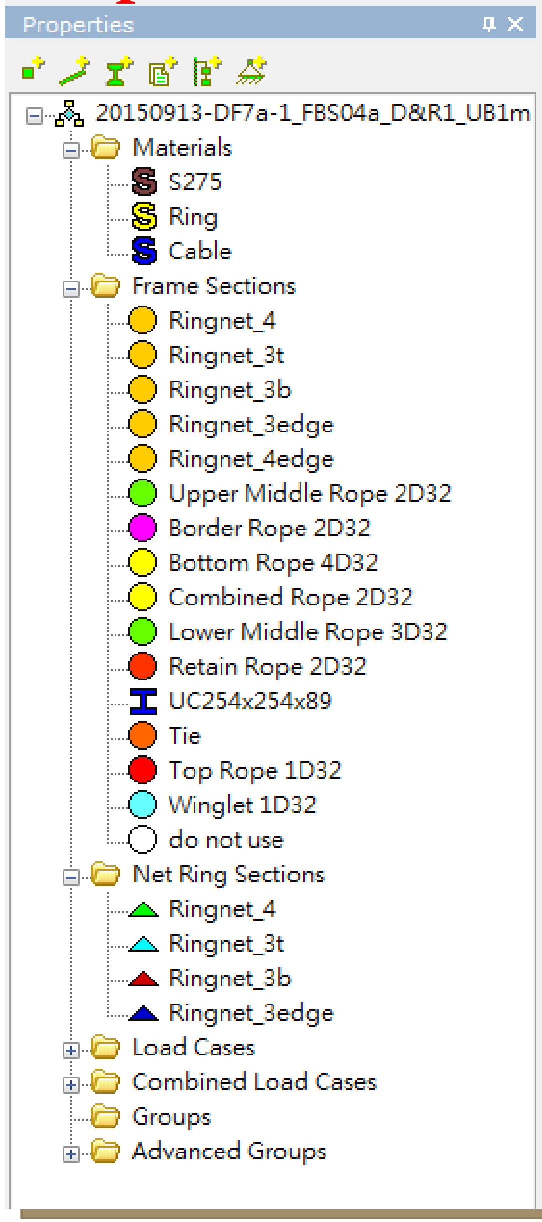


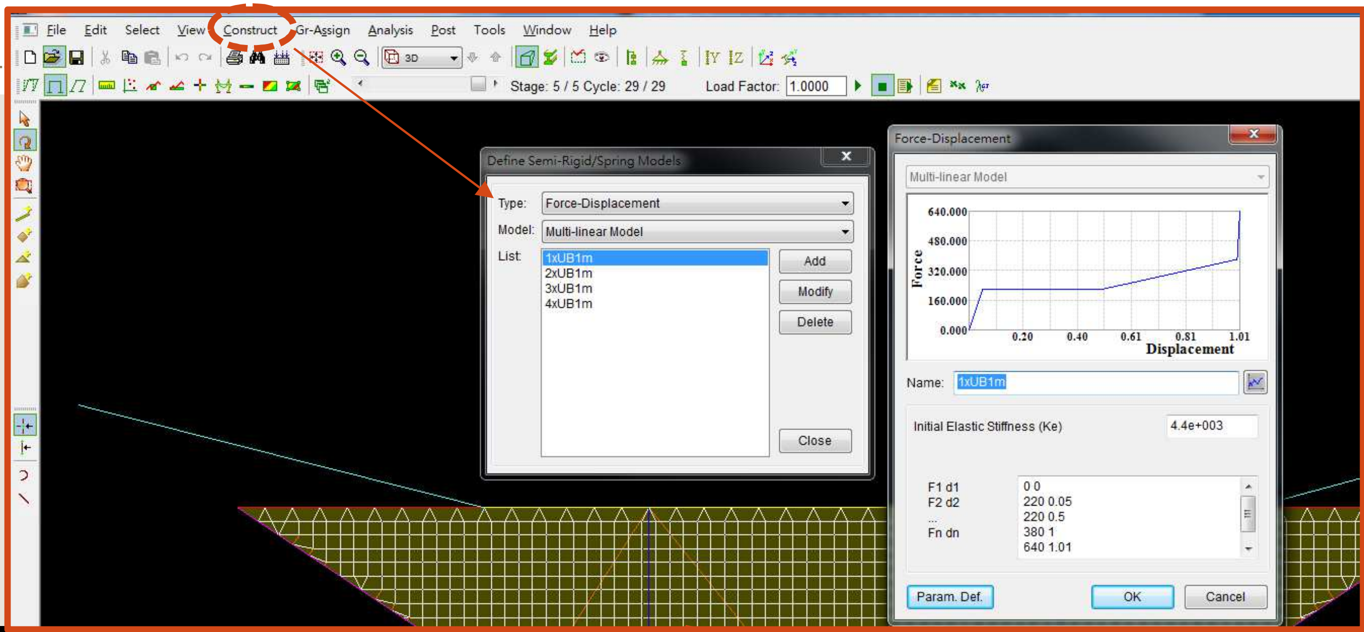


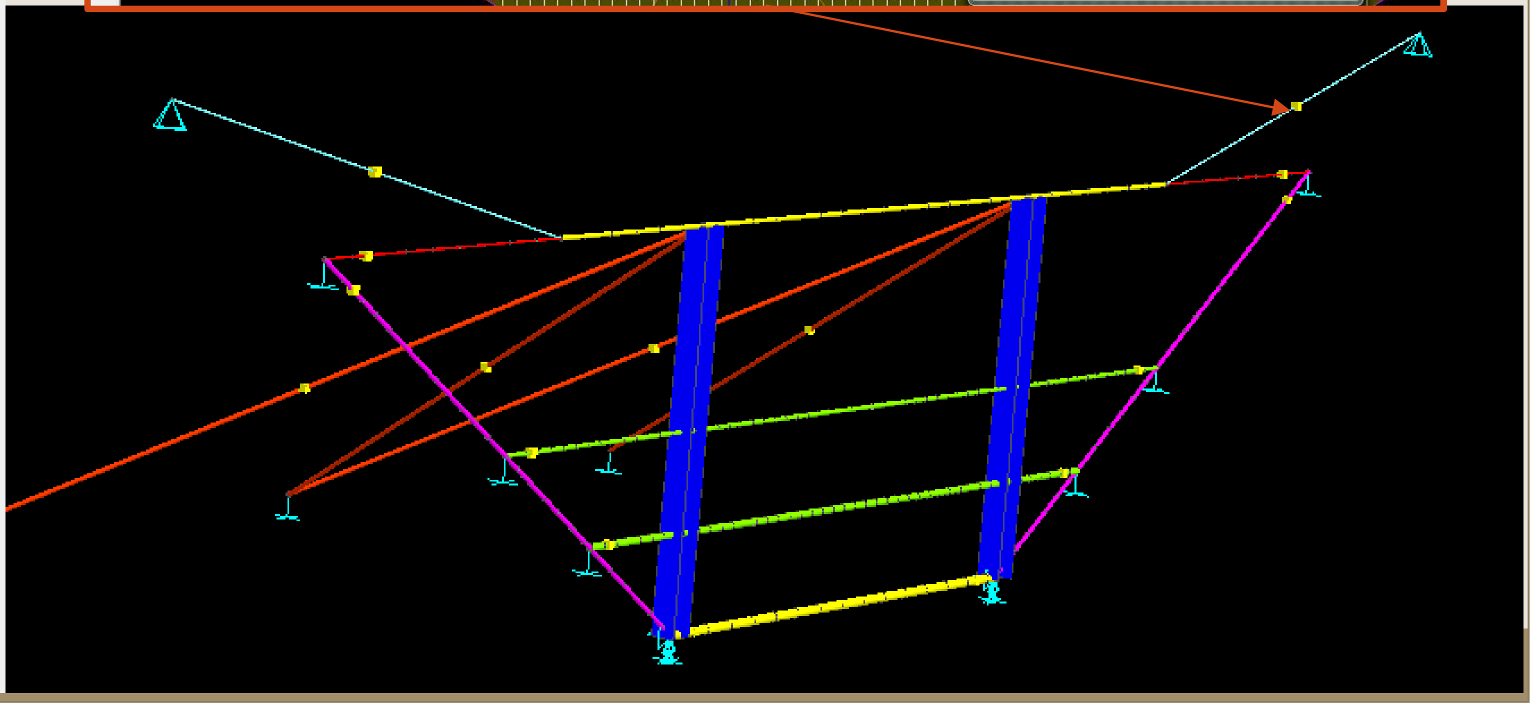
NIDA-MNN Model

Assign Brake Elements

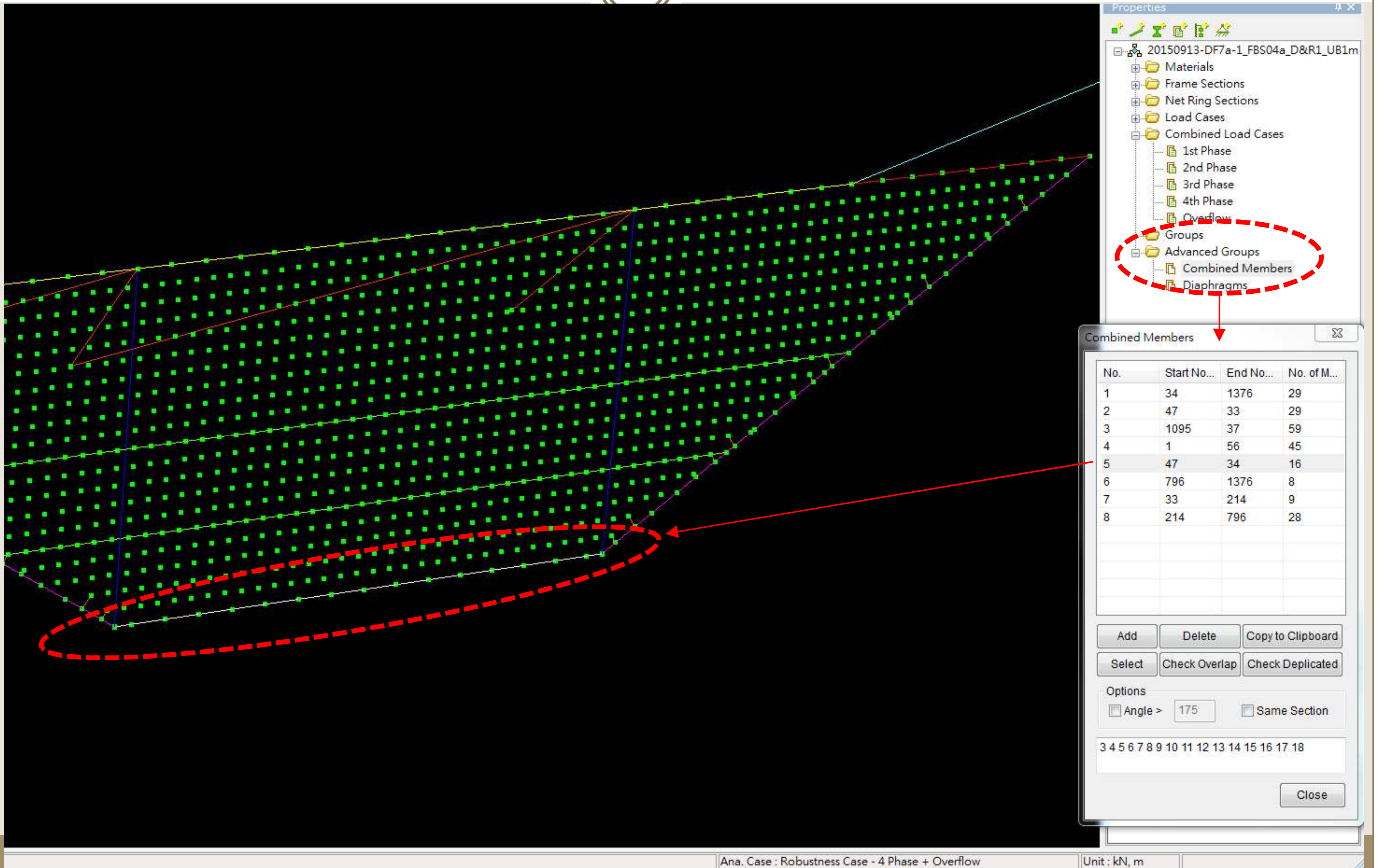
Material & Section Properties





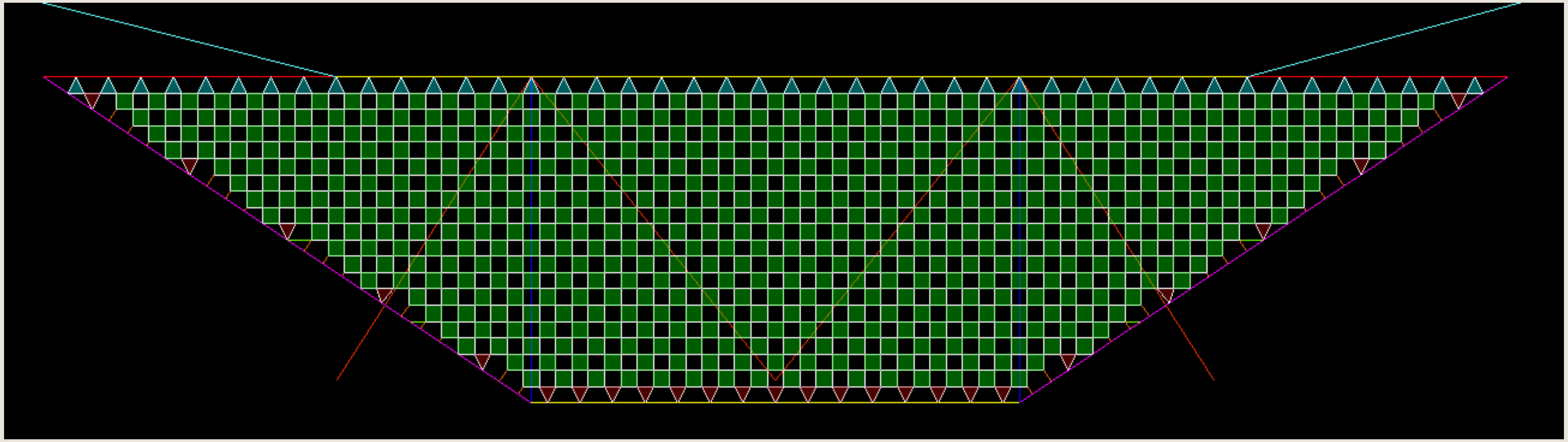


A tricky issue

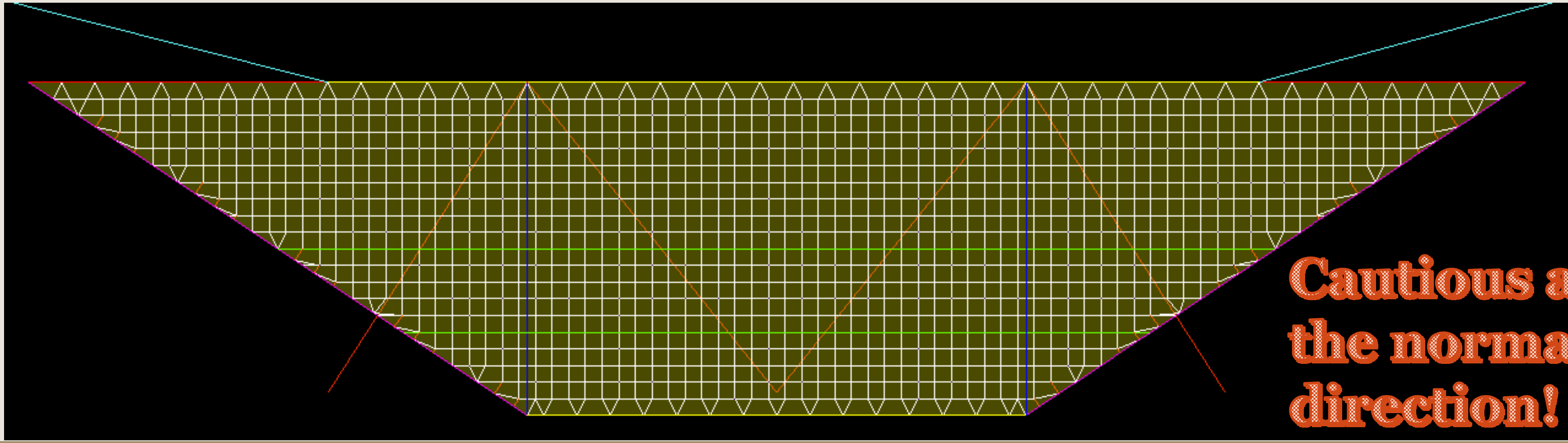


Loading Assignment

A full barrier model

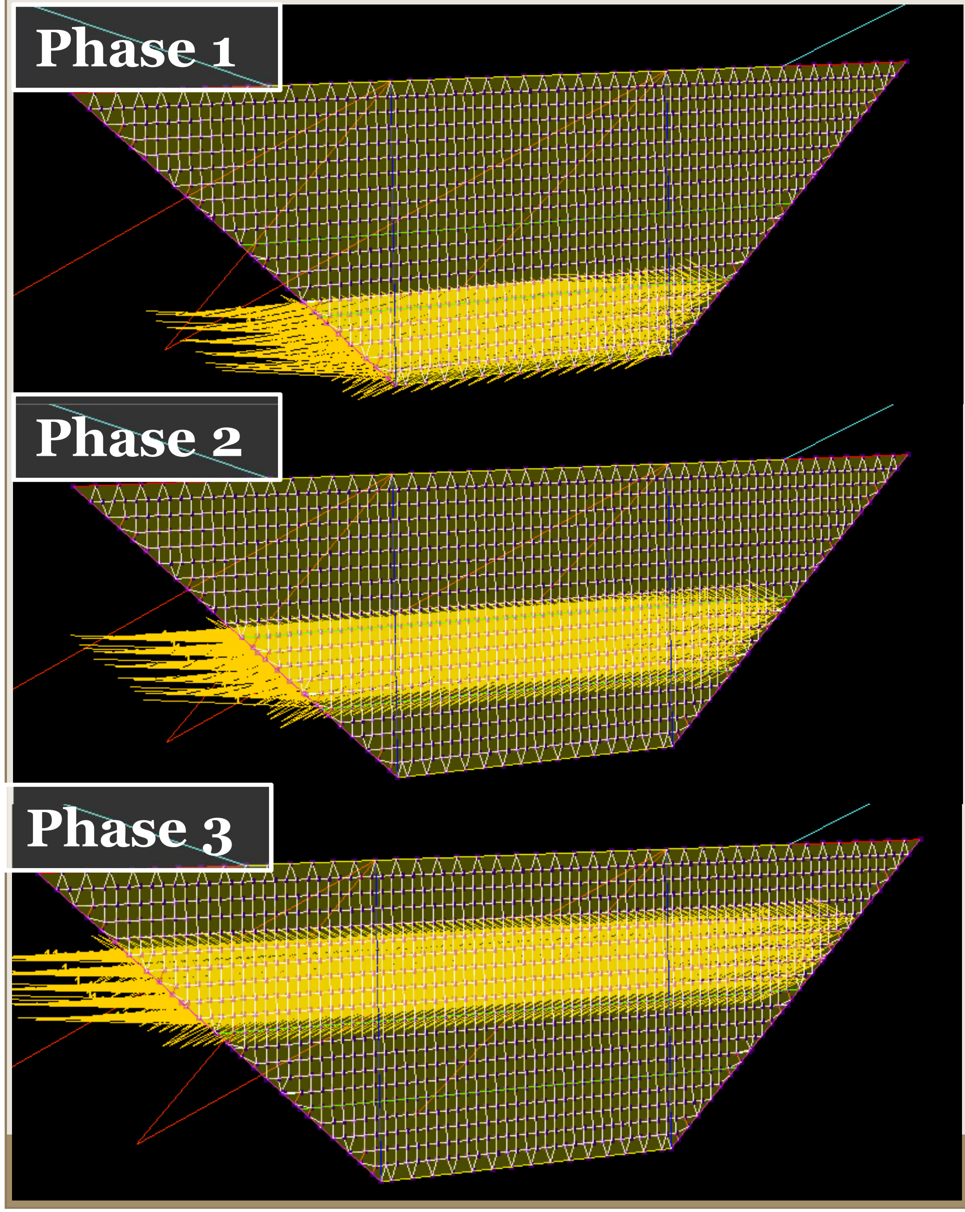


Use of floor element (for load assignment)

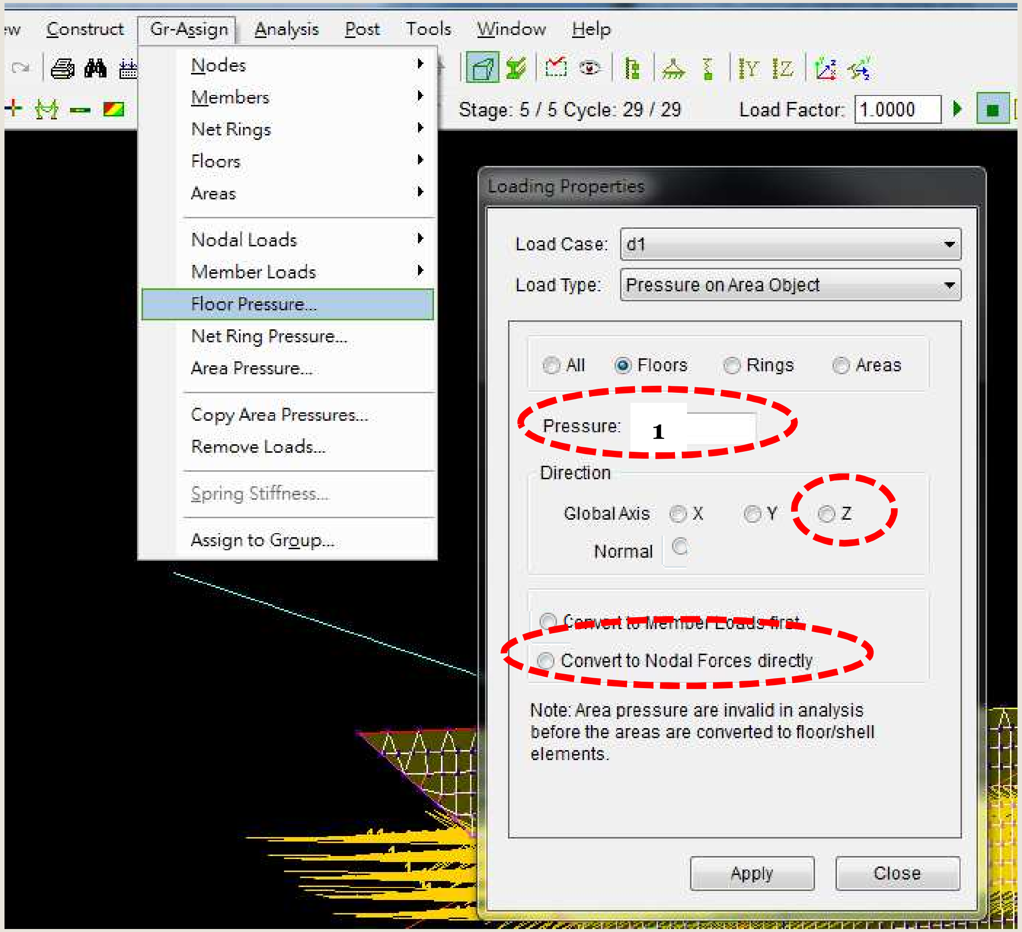


Cautious about the normal direction!

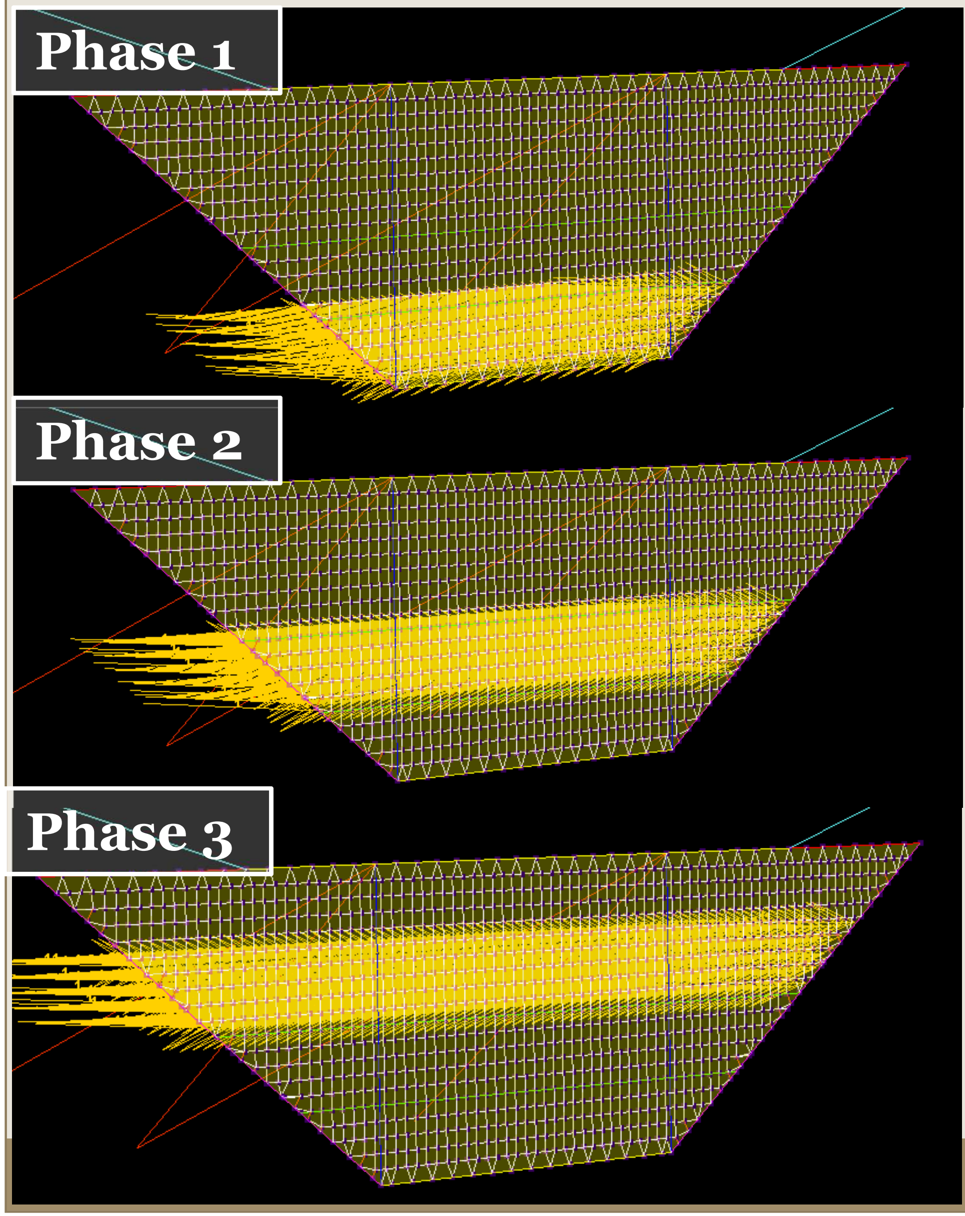
Loading Assignment

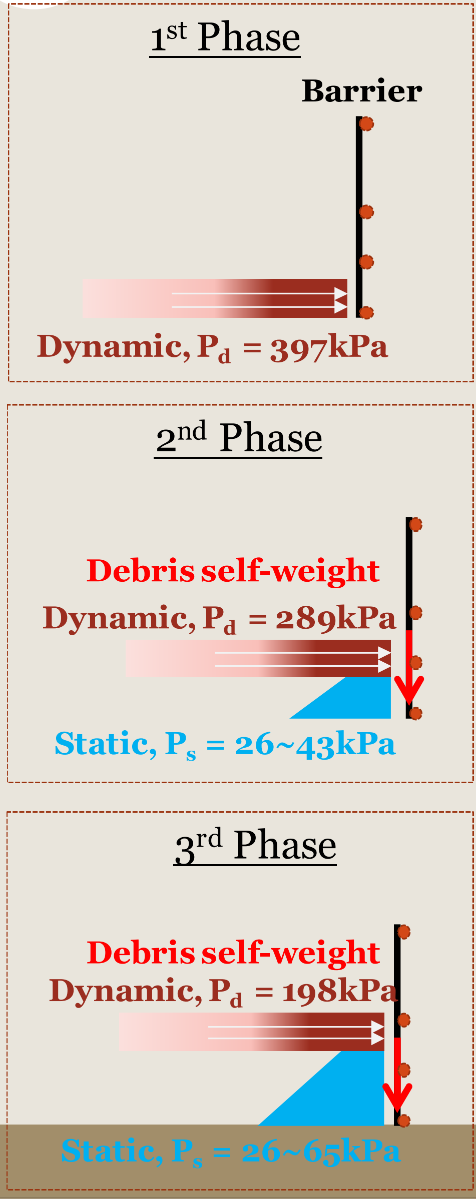


Only dynamic loadings are shown!



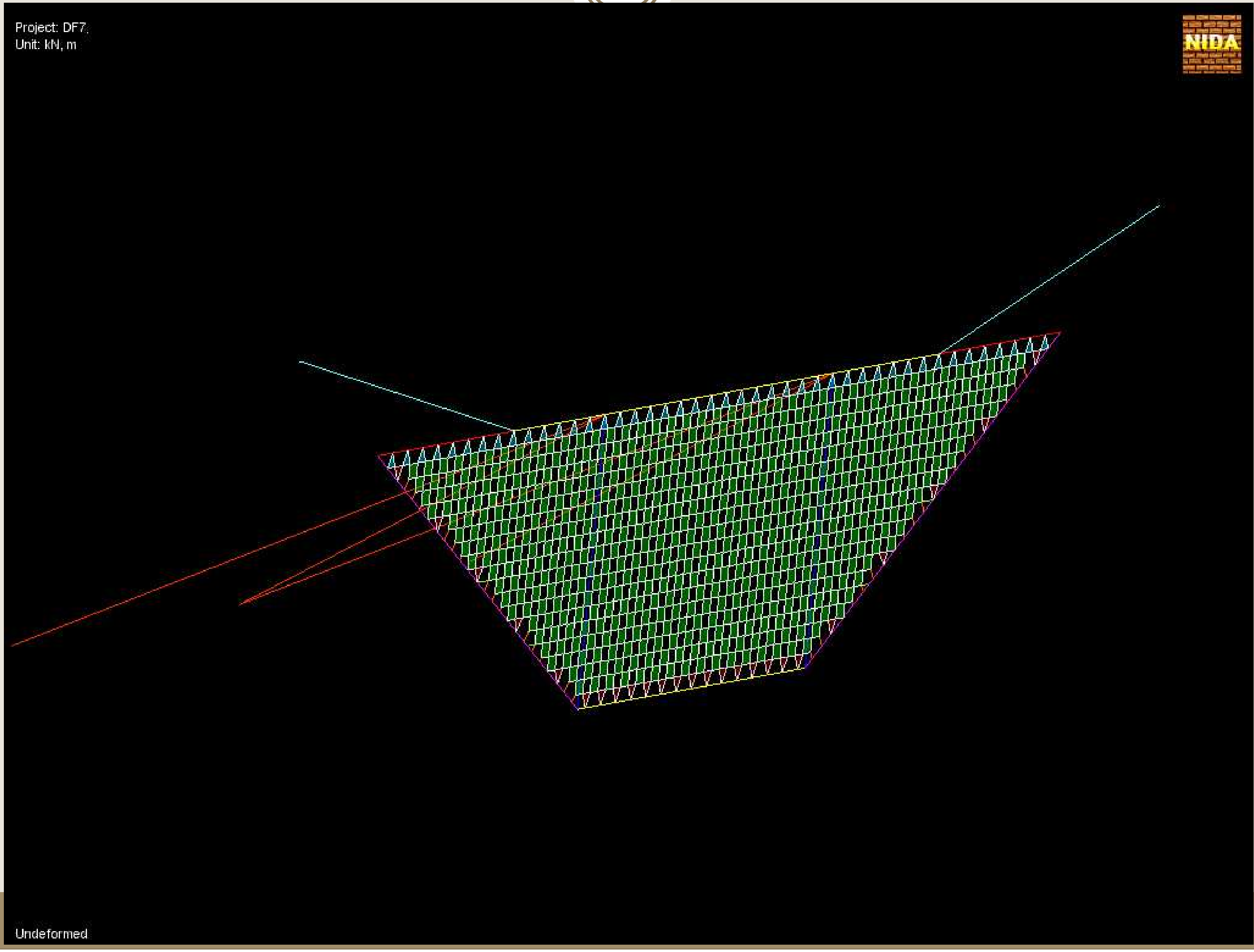
Loading Assignment





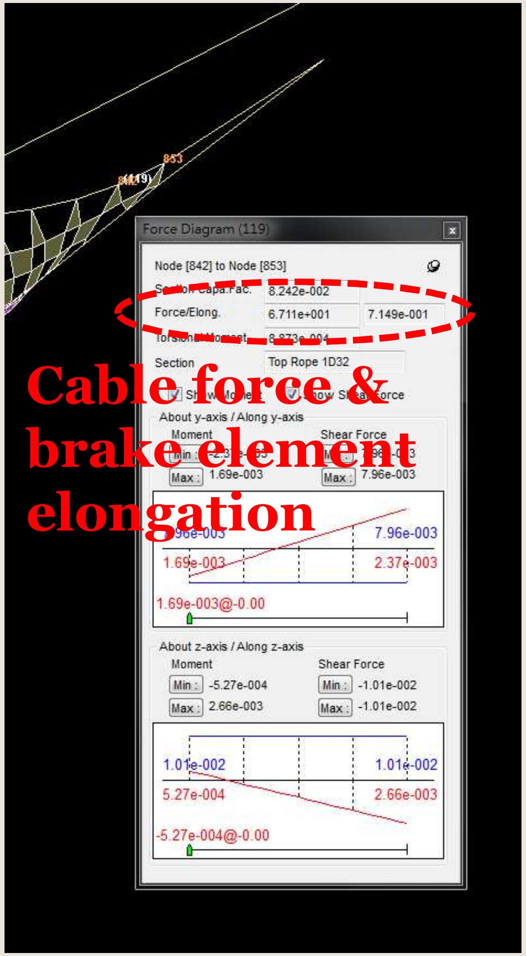
Cautious about the loading - unloading sequence when dynamic load changes to static load!

NIDA-MNN Model

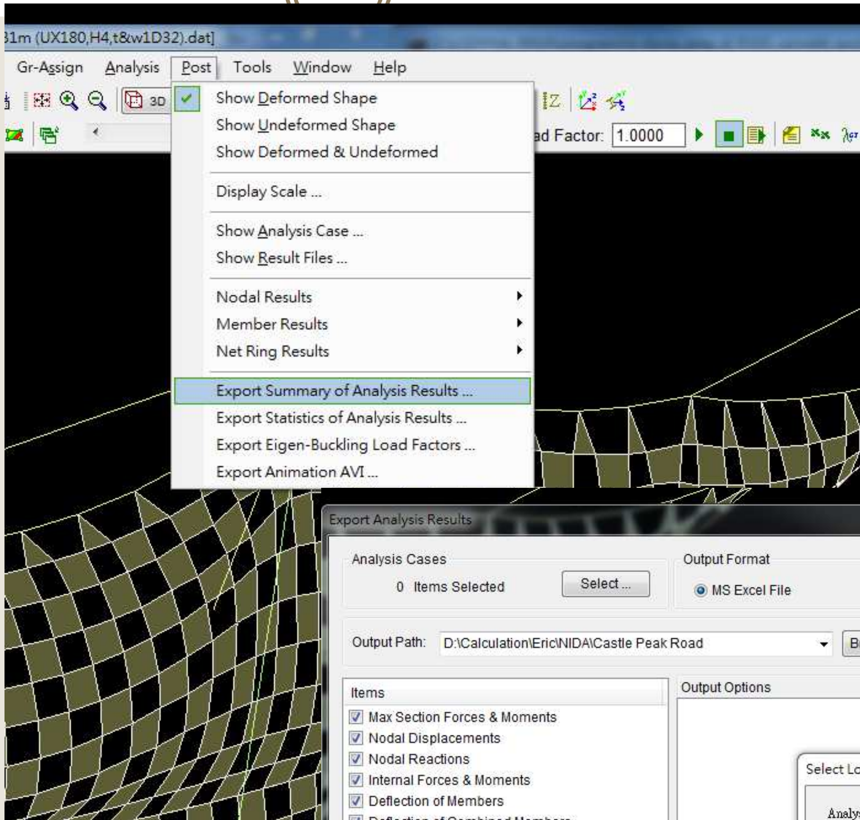


Read the Results

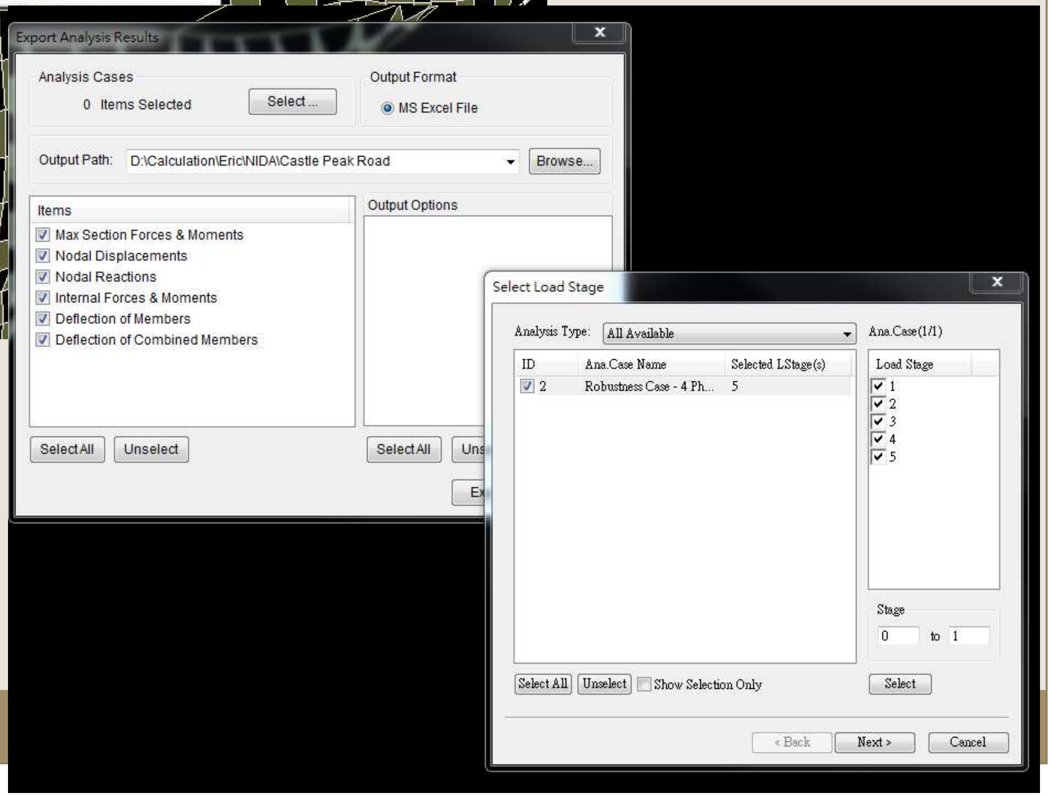
Read results of individual elements at a particular load step



Cable force & brake element elongation

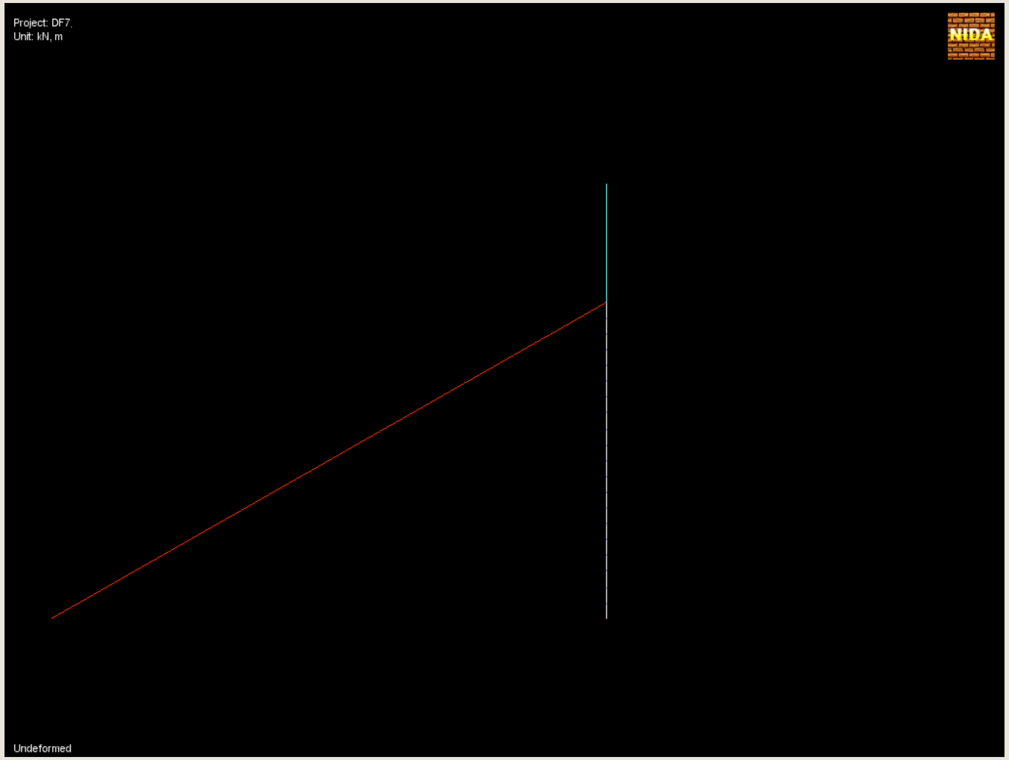


Export the results

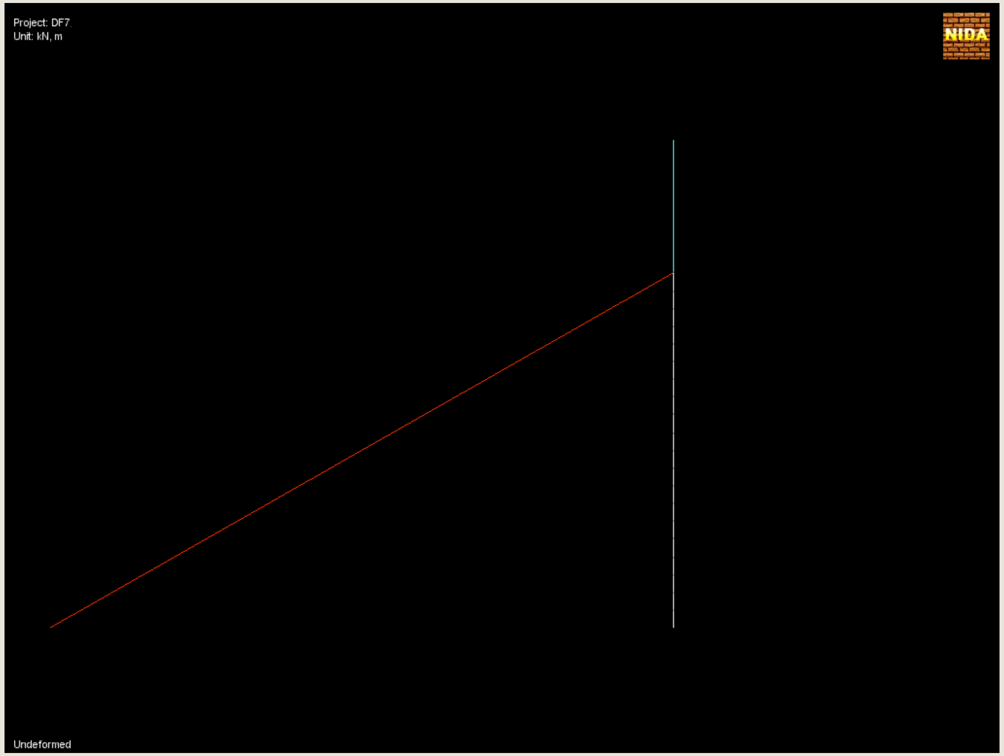


Lower Bound & Upper Bound Brake Element Curves

Lower Bound Brake Element



Upper Bound Brake Element



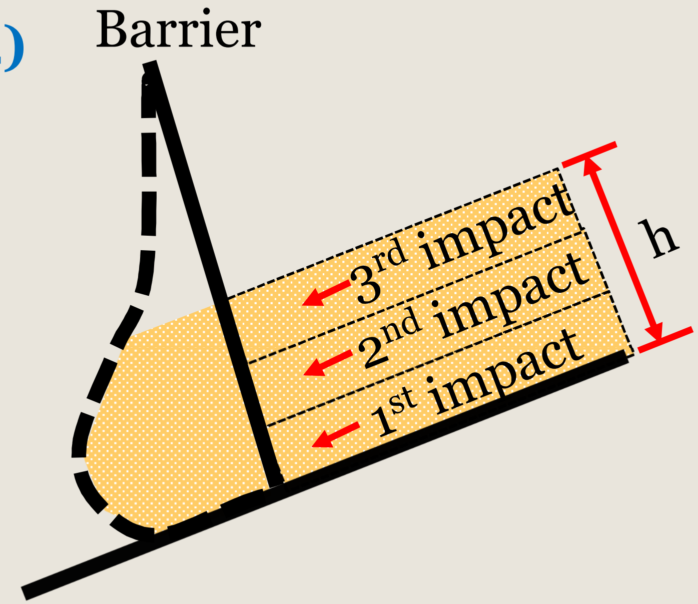
3. Design Optimisation using Coupled Analysis

Current Design Practice of Barriers

Force approach (GEO DN 1/2012)

$$P = \alpha \rho v_{max}^{2}$$

P is **pseudo-static** impact pressure on barrier
α **is empirical hydrodynamic coefficient**
(**design α = 2.0 for flexible barrier**)
ρ is density of debris
v is flow impact velocity
h is flow thickness



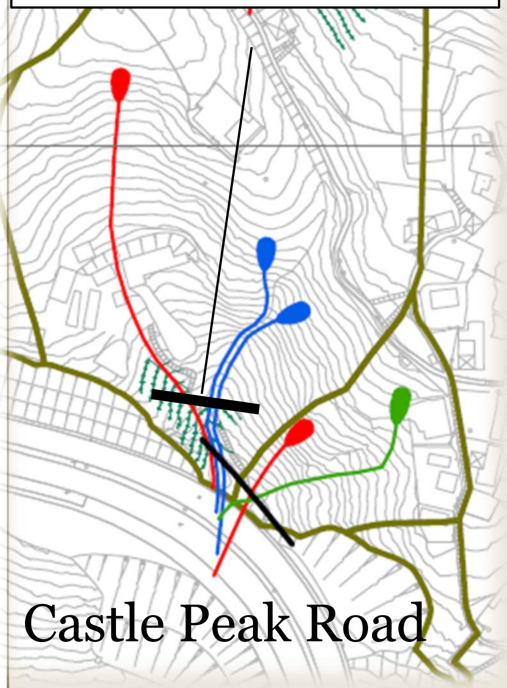
Why we need LS-DYNA?

- *Pseudo-static load ≠ Dynamic load*
- *Verify the coefficient "α = **2.0**" conservative or not*
- *Need a tool for explicit coupled analysis between landslide debris and barriers*

Case Study 1 – Flexible Barrier in Castle Peak Road

Mobility Results

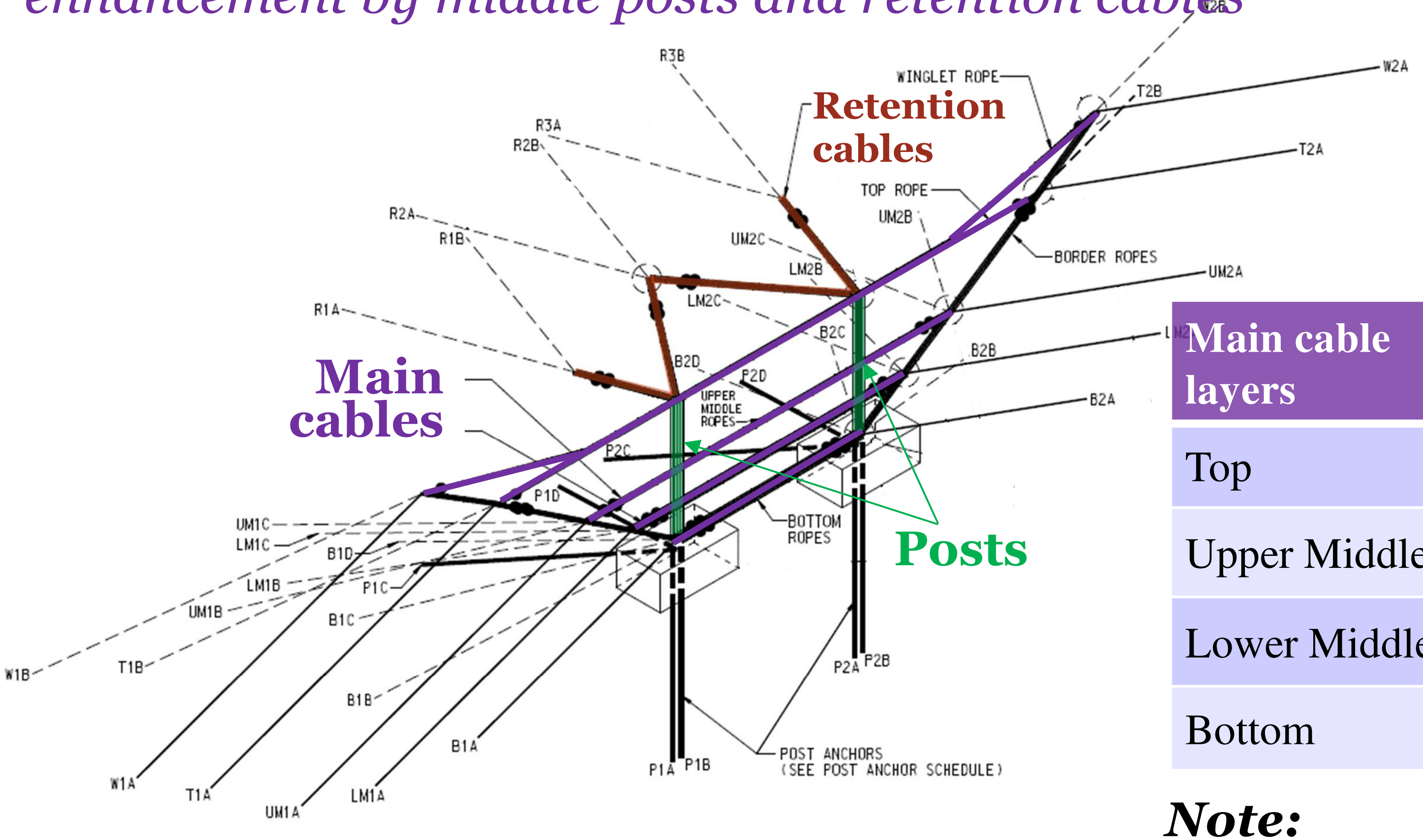
Design Volume = $150\ m^3$
Impact velocity = 9.5 m/s
Impact thickness = 1.0 m
Impact energy > 12,000 kJ



Design maximum impact pressure = 399 kPa based on force approach (DN 1/2012)

Barrier Design

Similar to Geobrugg side-anchored UX180 barrier with enhancement by middle posts and retention cables

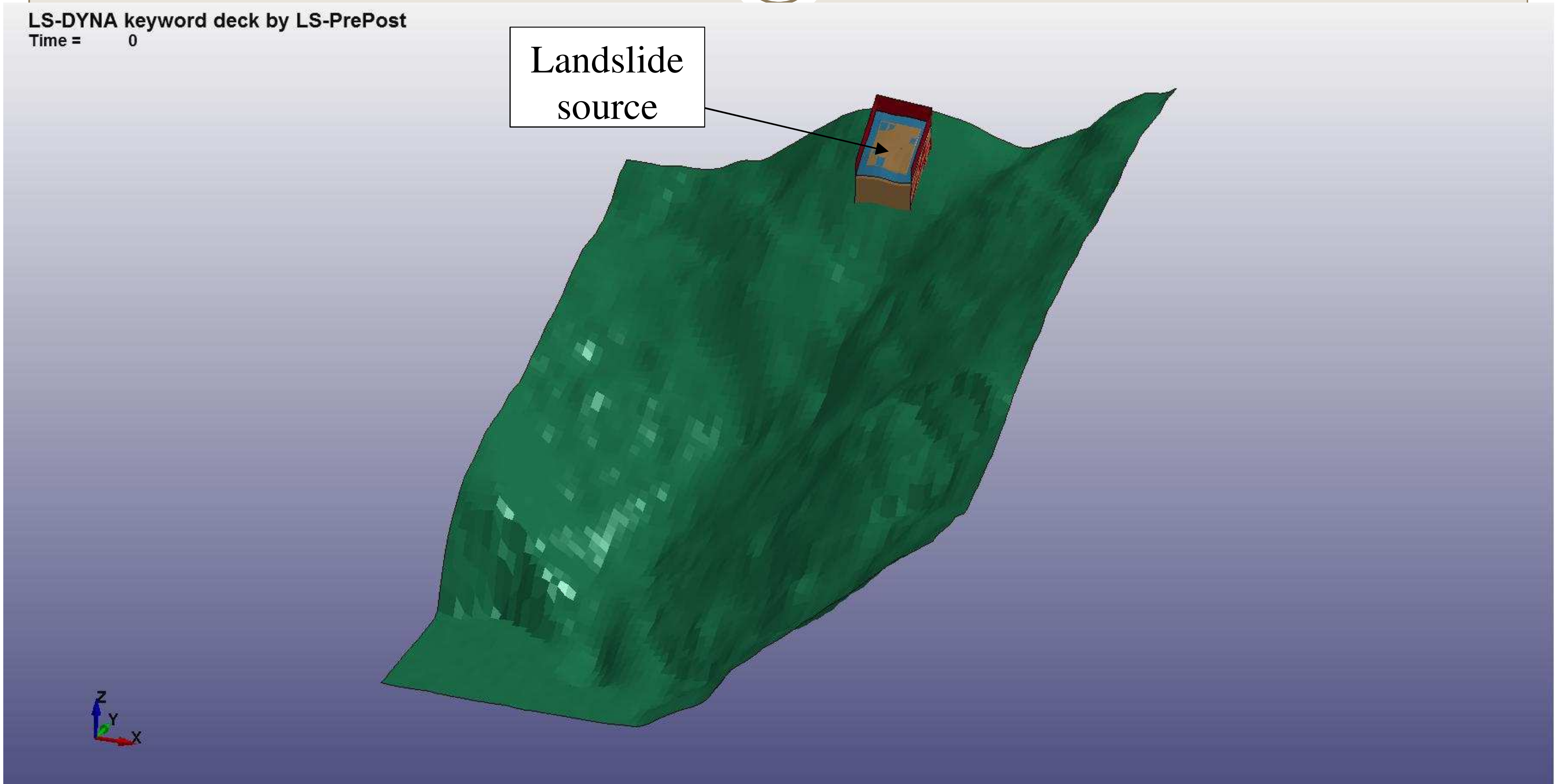


Main cable layers	Number of cables
Top	$1 \times 22\phi$
Upper Middle	$2 \times 22\phi$
Lower Middle	$3 \times 22\phi$
Bottom	$4 \times 22\phi$

- **5 m tall side-anchored flexible barrier**
- **Maximum 4 nos. of ground anchors at foundation**

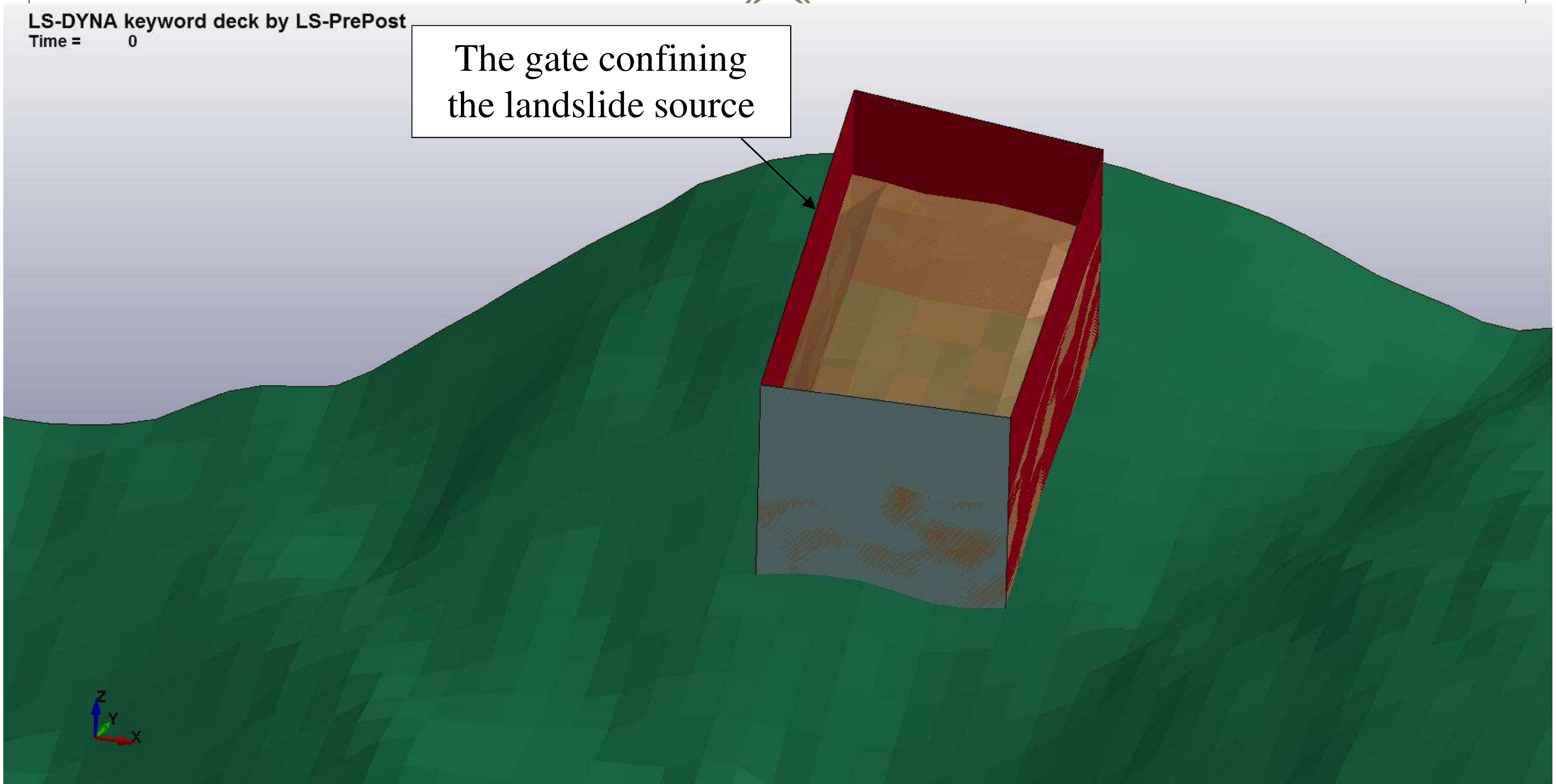
Note:
Structural members and details are designed by ASD

Numerical Modelling Using LS-DYNA

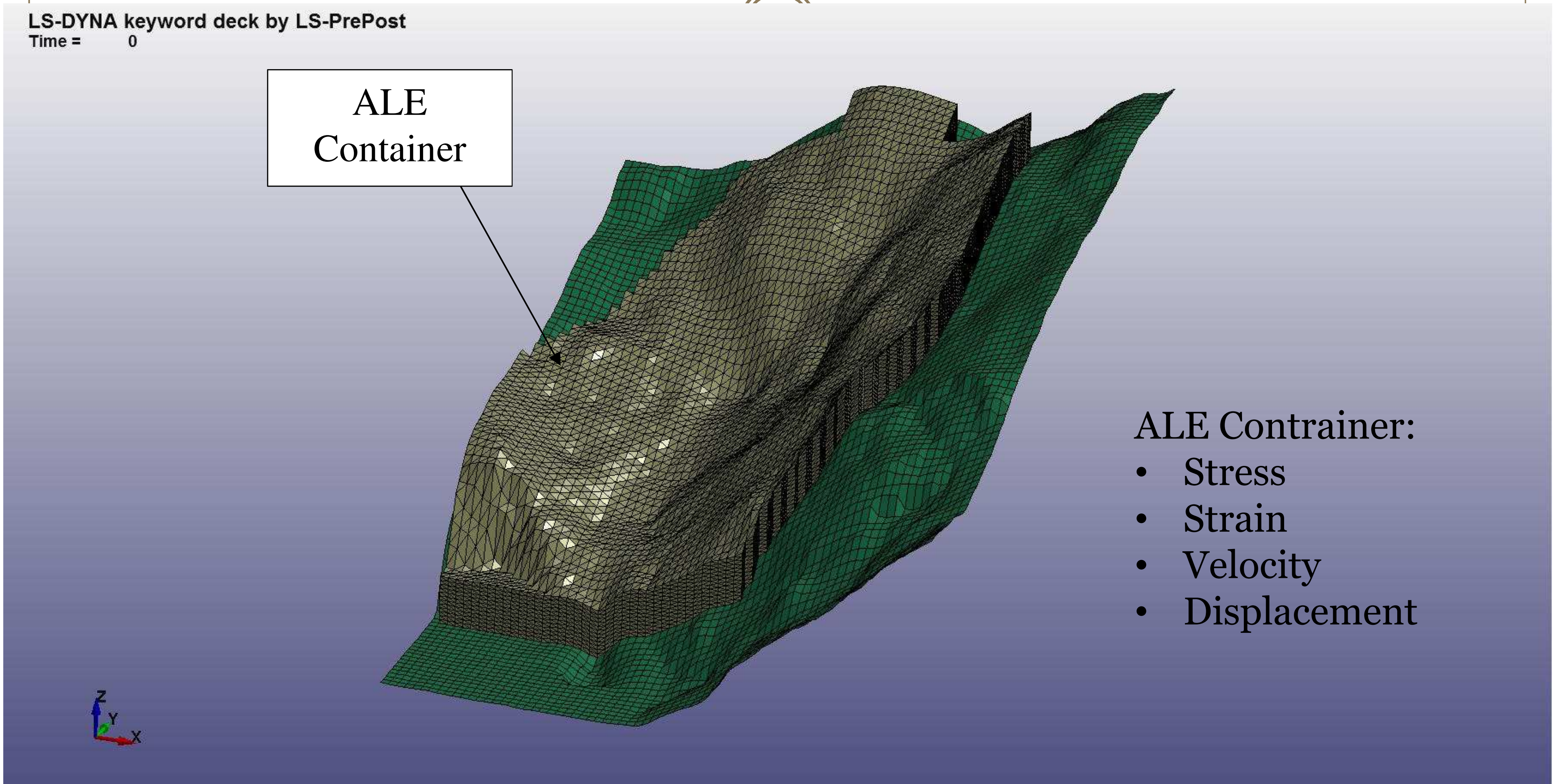


Collaboration with Arup

Numerical Modelling Using LS-DYNA



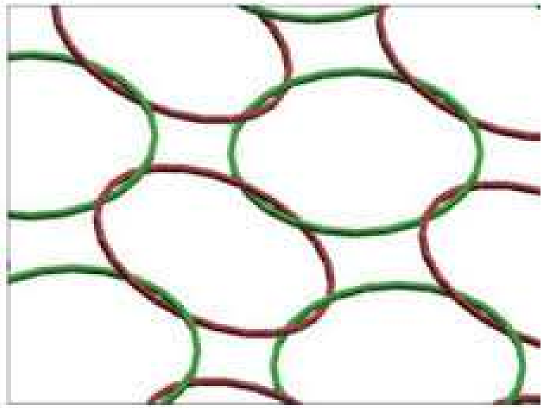
Numerical Modelling Using LS-DYNA



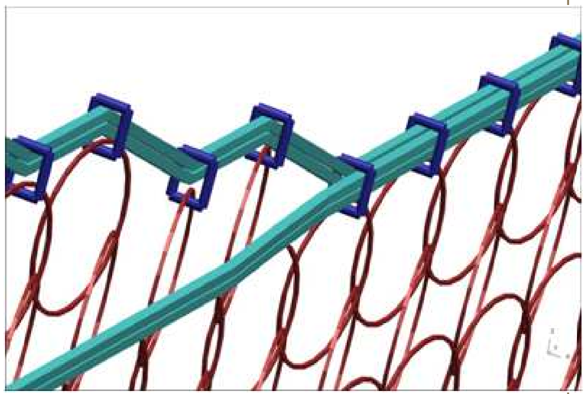
Numerical Modelling Using LS-DYNA

- ## Flexible Barrier

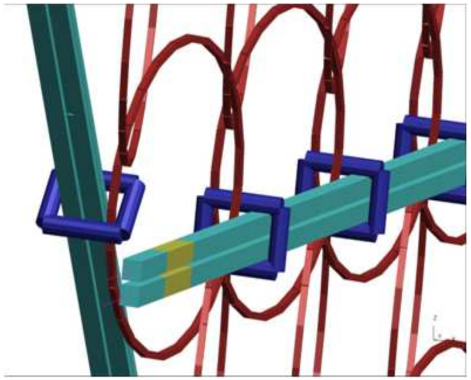
Explicit modelling as elastic beam elements



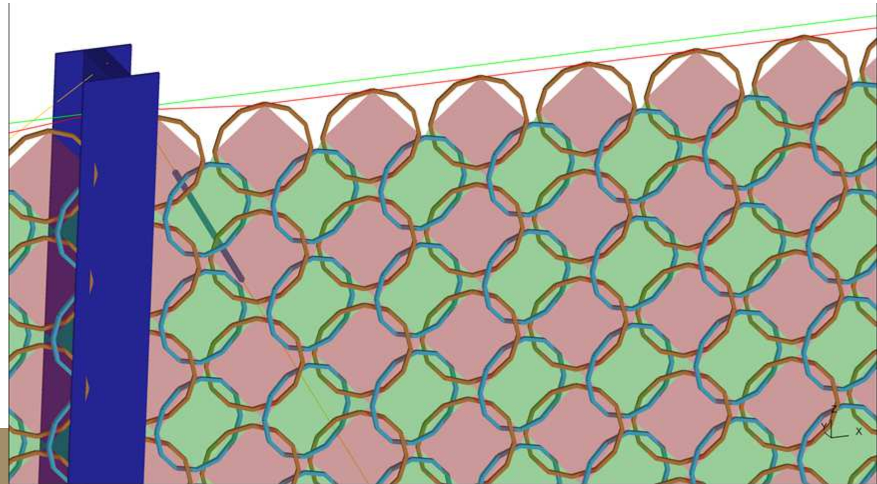
Sliding contacts

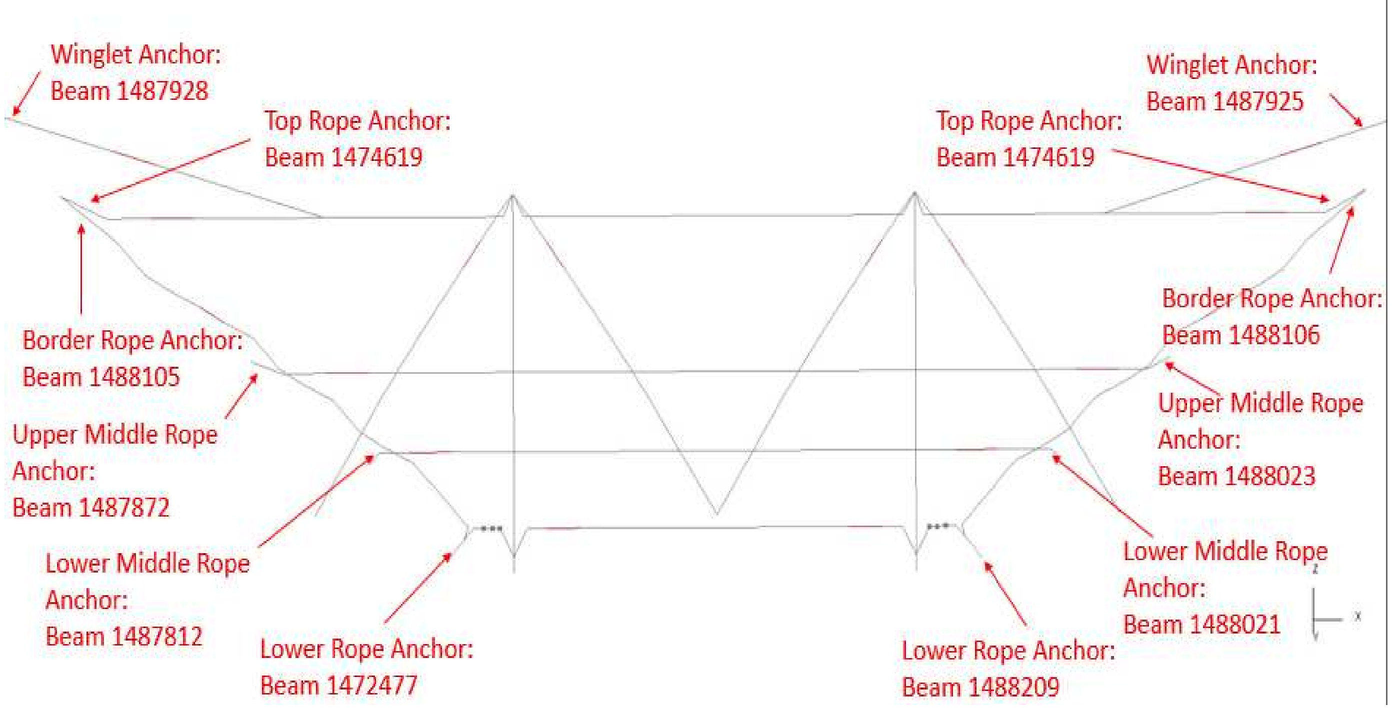


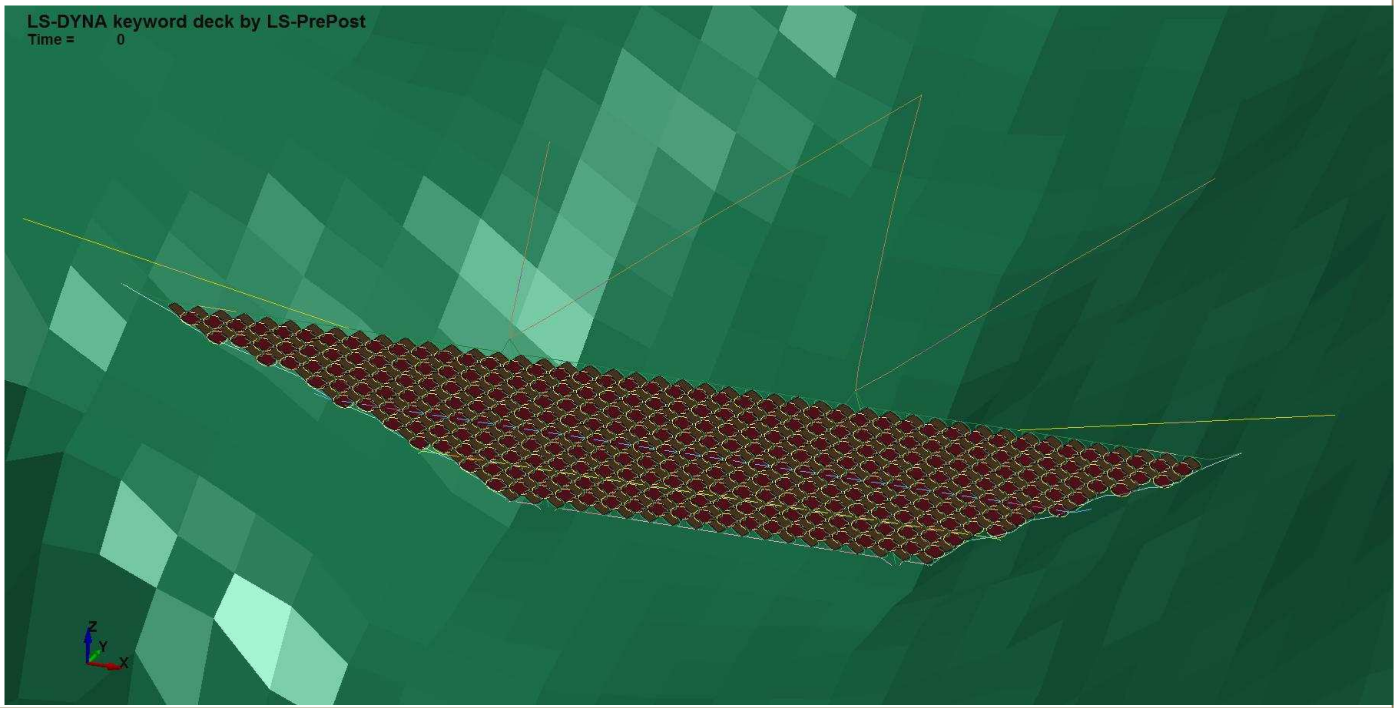
Brake elements



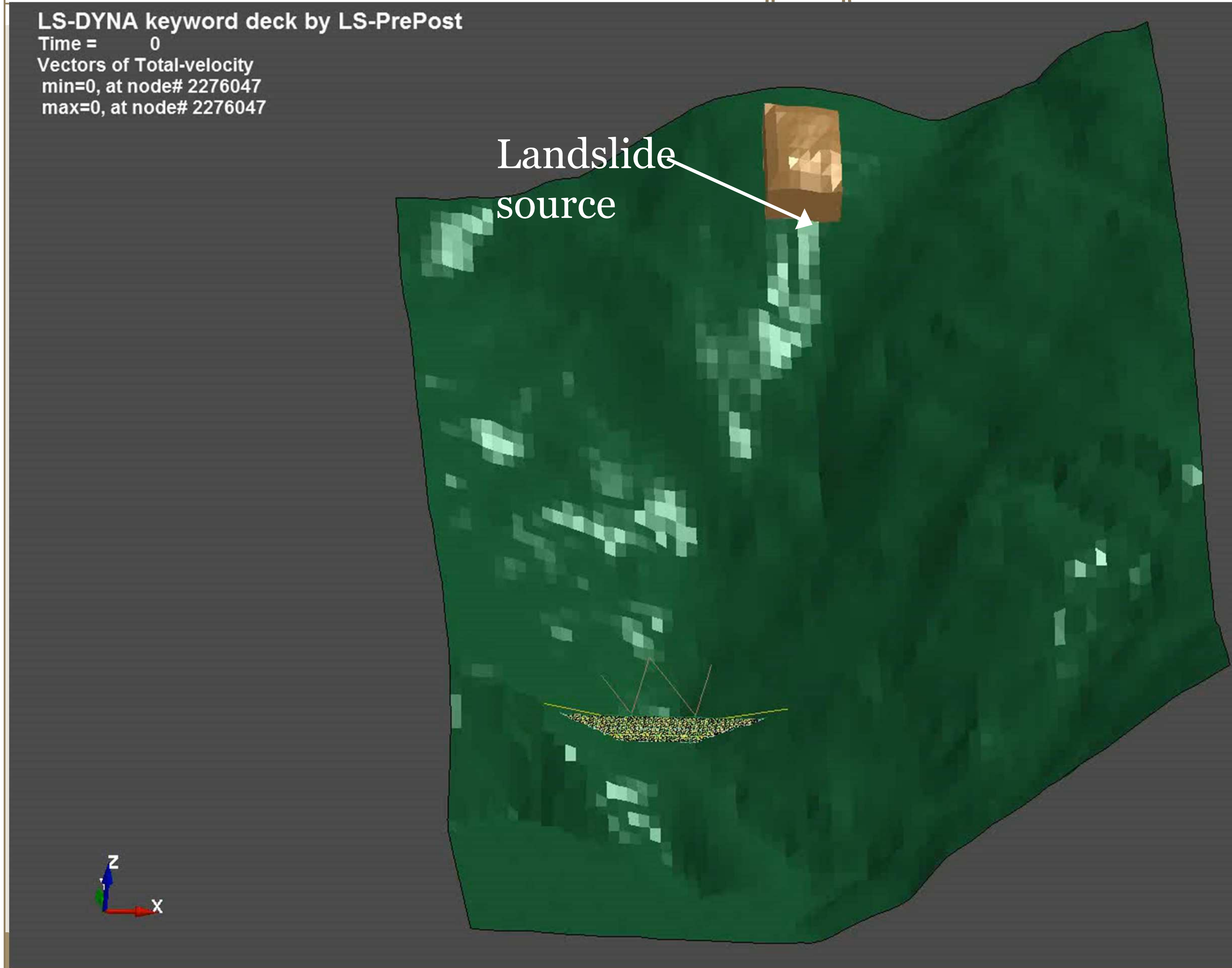
"Null" shell membrane




Winglet Anchor:
Beam 1487928
Top Rope Anchor:
Beam 1474619
Border Rope Anchor:
Beam 1488105
Upper Middle Rope
Anchor:
Beam 1487872
Lower Middle Rope
Anchor:
Beam 1487812
Lower Rope Anchor:
Beam 1472477
Top Rope Anchor:
Beam 1474619
Winglet Anchor:
Beam 1487925
Border Rope Anchor:
Beam 1488106
Upper Middle Rope
Anchor:
Beam 1488023
Lower Middle Rope
Anchor:
Beam 1488021
Lower Rope Anchor:
Beam 1488209


LS-DYNA keyword deck by LS-PrePost
Time = 0

LS-DYNA Simulation
Dynamic Coupled Analysis

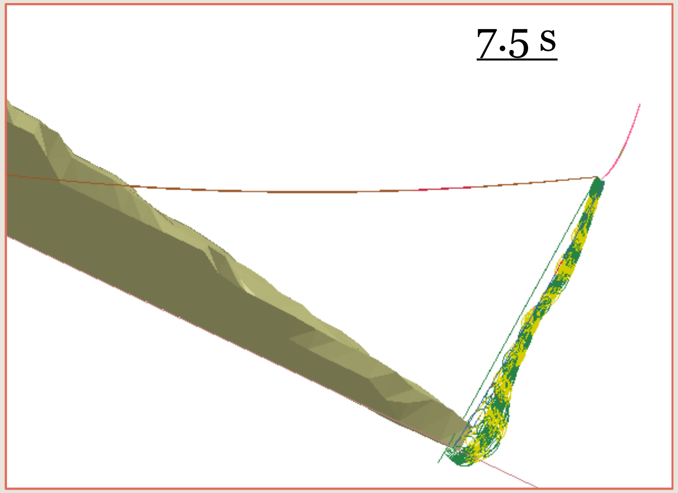


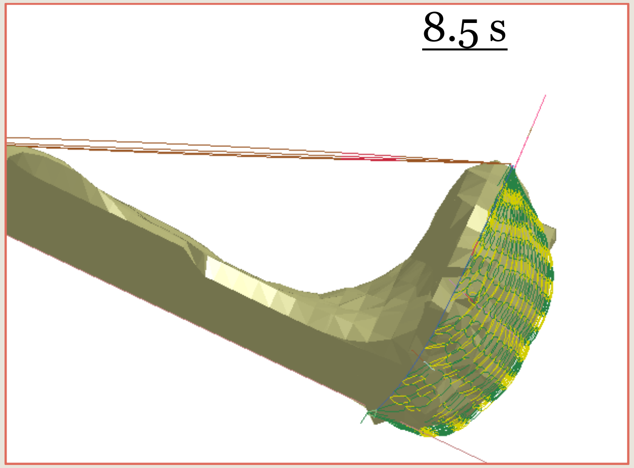
Coupled modelling with debris mobility and flexible barrier

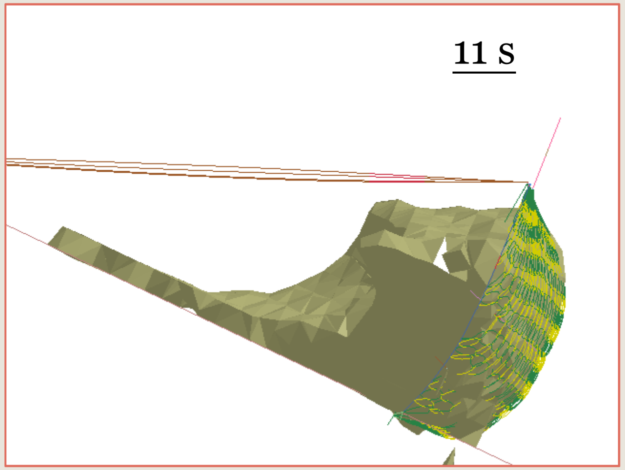
Dynamic Coupled Numerical Simulations

Program LS-DYNA

Observed pile-up mechanism (TN1/2012)



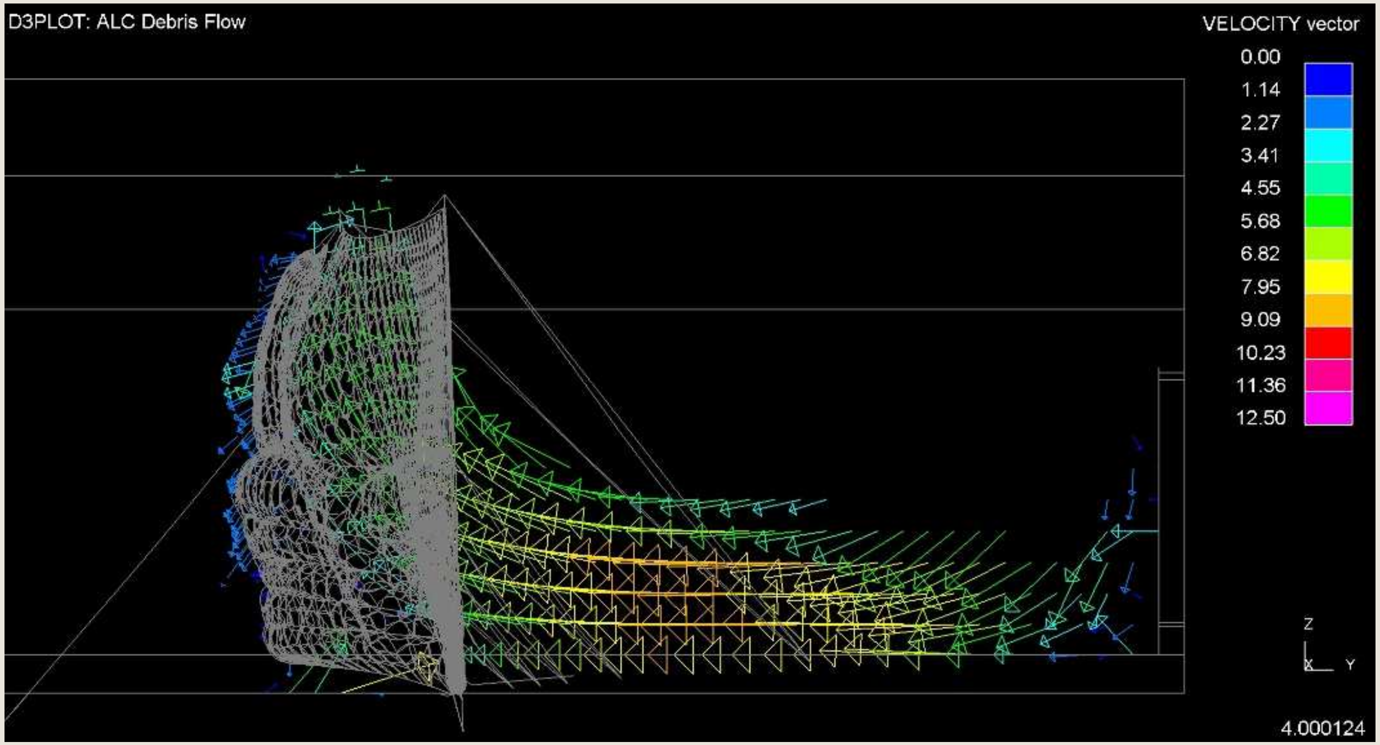




Debris-barrier Interaction

Coupled analysis approach

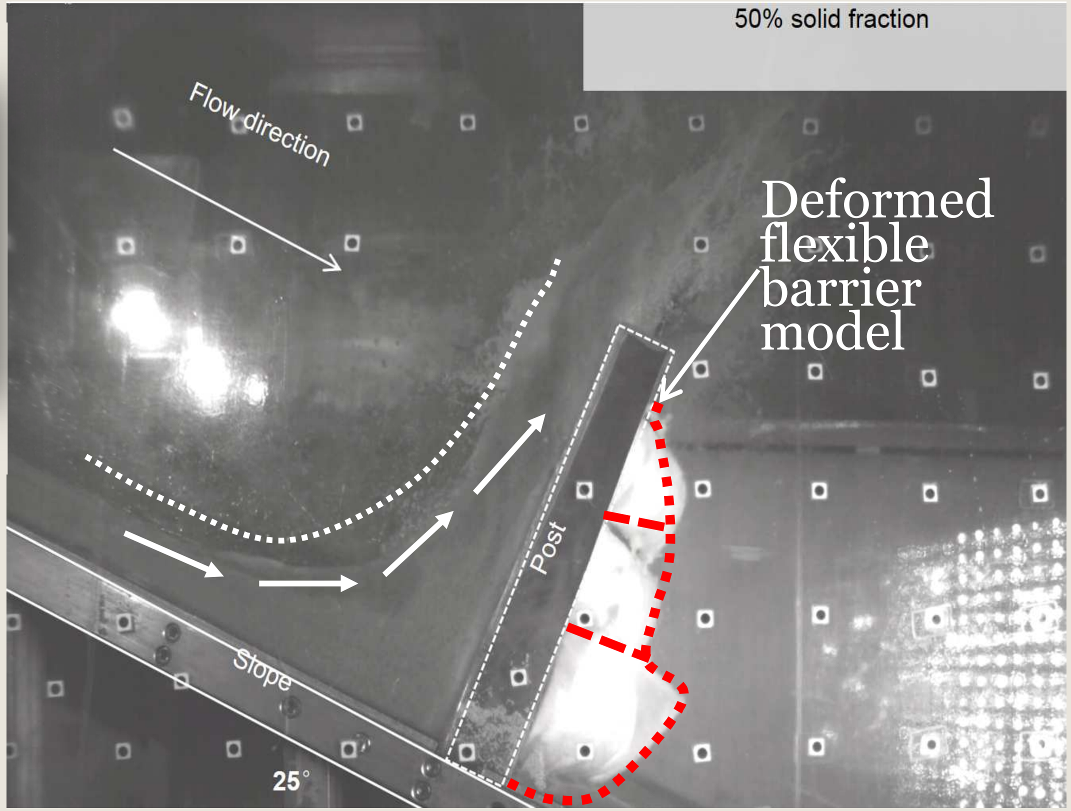
- Enhance understanding on the performance of flexible barrier
  - Energy loss of debris internal shearing
  - Redirection of debris impact momentum after impact



Debris-barrier Interaction

Similar observation from the findings of the centrifuge tests

100 x gravity (g)



Further verification tests to be carried out in large-scale flume by S&T

Kinetic energy is dissipated by redirection of momentum and internal shearing of particles during impact.

THANK YOU