Teknologidagene 2018

Research center for smart submerged floating tunnel system

H.K. Lee
Dept. of Civil and Environment Engineering
Korea Advanced Institute of Science and Technology (KAIST)

November 1, 2018

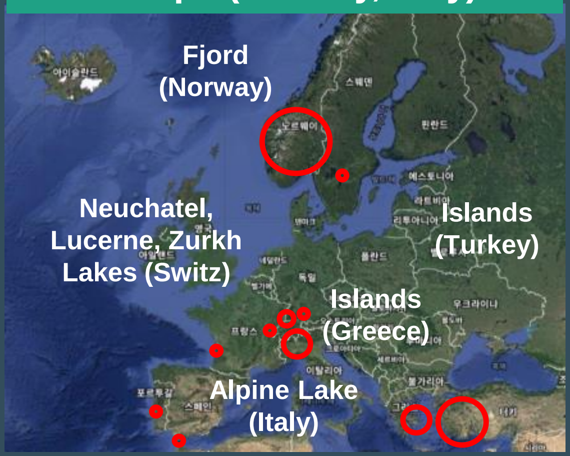
NRF 한국연구재단 National Research Foundation of Korea
KAIST
Smart SFT Submerged Floating Tunnel System

Background

- **Growing interest in SFT** around the world: being considered as a candidate for a fixed link for many crossings.
- In case of Korea, SFT is not only a **suitable as a solution for a number of fixed links** (between China-Korea, Korea-Japan), it is expected to **boost economy and promote logistics industries in the connected countries**.
- Against this backdrop, Research Center for Smart Submerged Floating Tunnel Systems was established at KAIST in 2017, funded by National Research Foundation of Korea, Ministry of Science and ICT.

Candidates for SFT

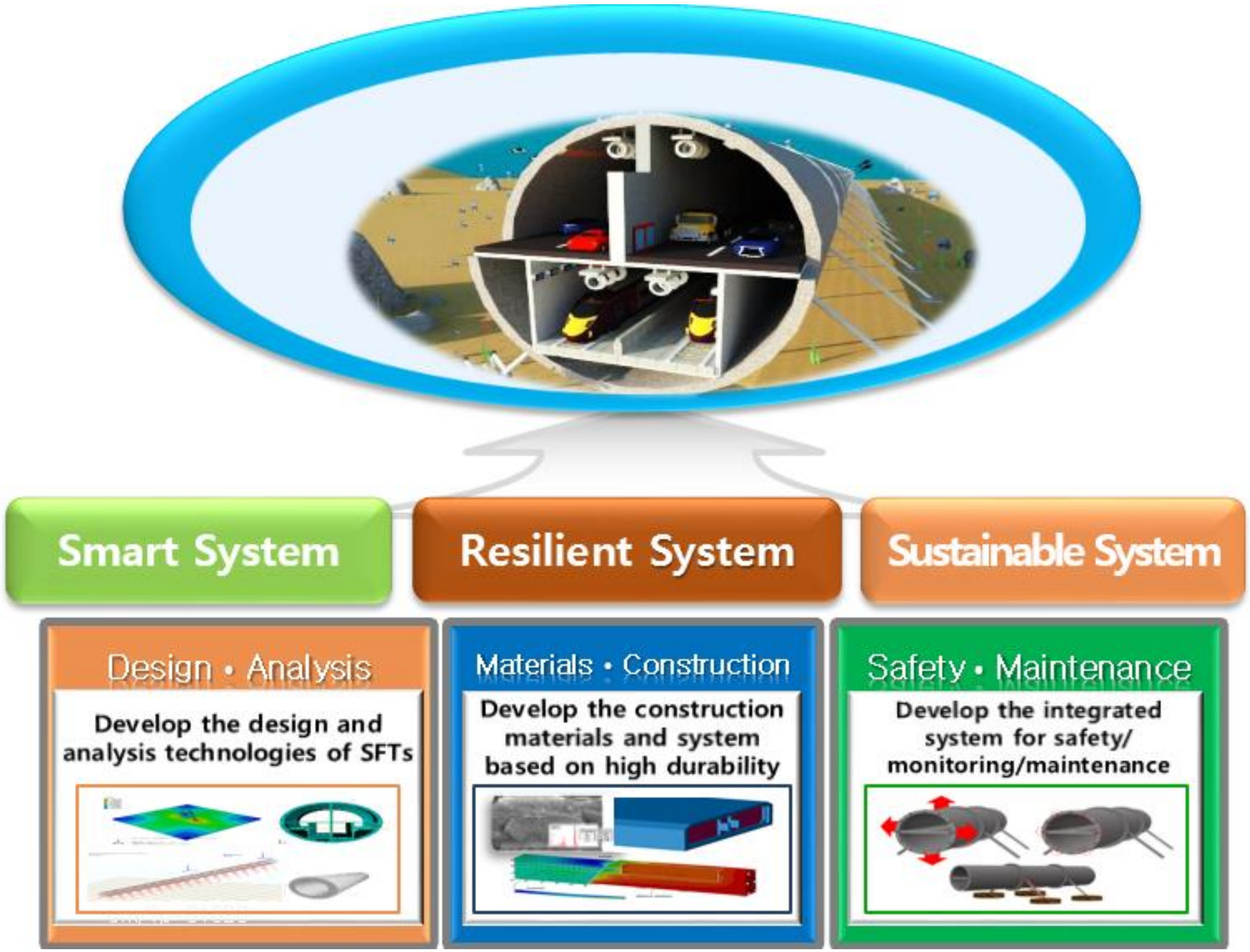
Europe (Norway, Italy)



North America (USA, Canada)

Asia (China, Korea, Japan)

Goal of the center



Develop ***fundamental technologies for SFTs***

considering smartness, safety, and sustainability

Brief history

2017

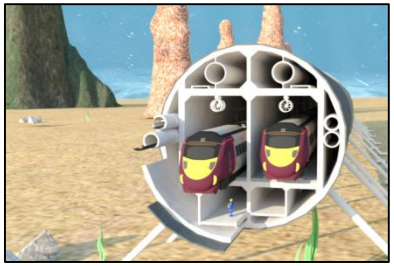

Memorandum of Understanding
Between
Research Center for
Smart Submerged Floating Tunnel System of KAIST
and
Norwegian Geotechnical Institute

Signed MOU with TAMU and Norwegian Geotechnical Institute

Mar 2

Jun 1

Official launch of the center, grant funded by NRF



Kick-off meeting at KAIST, celebrating successful launch of the Center

Sep 7

2018

Jan 29

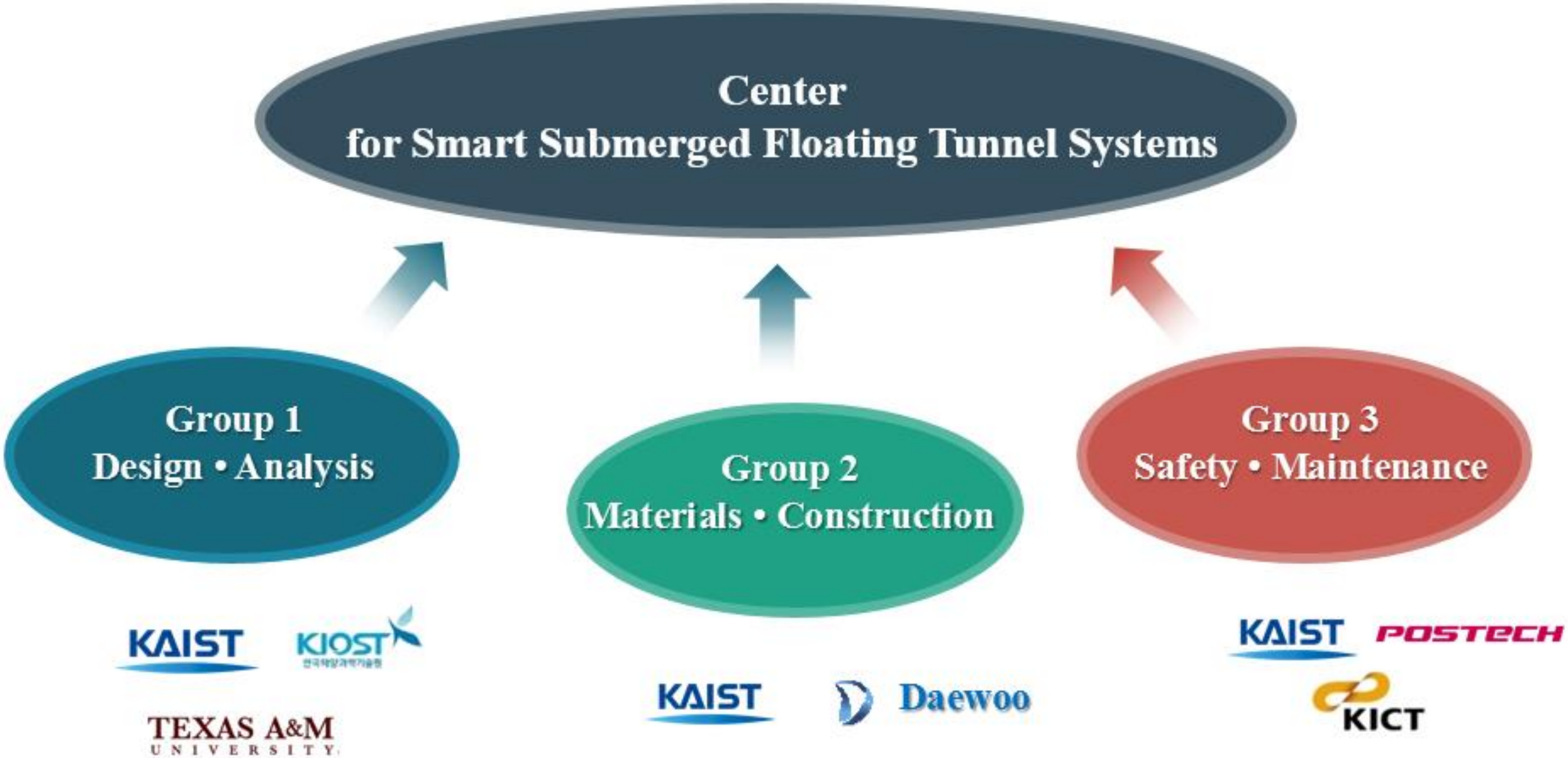
International Workshop on Smart SFTs hosted by Center in Busan, jointed with **1st Year Winter Workshop** on Smart SFTs

2nd Year Summer Workshop on Smart SFTs, held in Jeju

Jun 20

2019

Organization

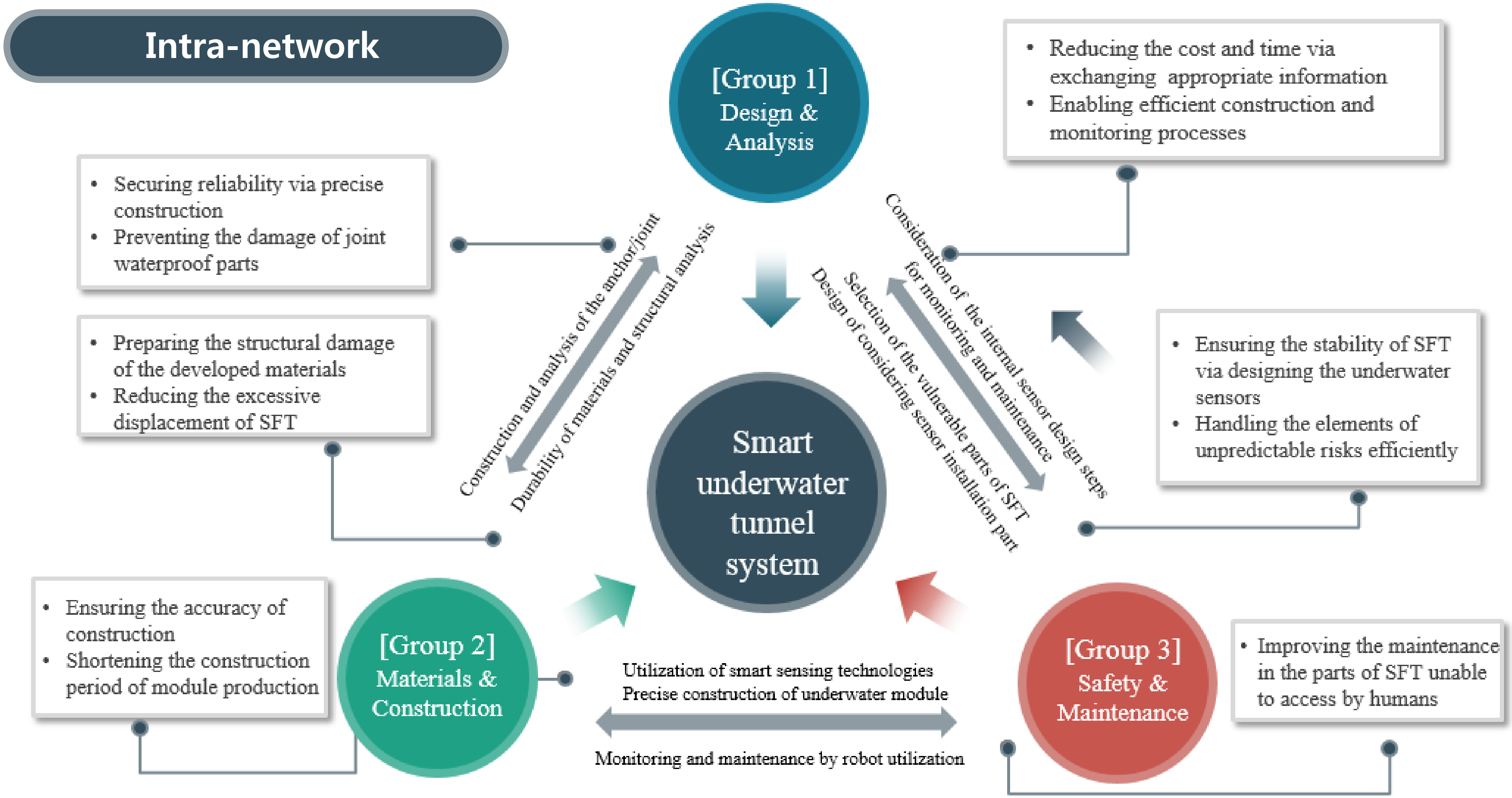


- ➢ The center consists of three groups covering different topics of research areas.
- ➢ Each group is comprised of 3-5 sub-groups led by professors and researchers from University/research institute/industry.

Center research outline

	Group 1 Design · Analysis Technology	Group 2 Materials · Construction Technology	Group 3 Safety · Maintenance Technology
1st Step Goal (2017.06-2021.02) Develop Core Fundamental Technologies	Build up core fundamental technologies for the design and analysis of SFTs	Develop core fundamental technologies for enhancing durability and construction process of SFTs	Obtain core fundamental technologies for ICT based safety, monitoring, and maintenance
2nd Step Goal (2021.03-2024.02) Performance Verification& Technology Transfer (Pilot Test)	Develop the design and analysis technologies for the pilot test of SFTs	Produce module structure and optimize construction in empirical environments	Verify and integrate the developed technologies via pilot tests

Cooperative research plan



➢ Improve the maturity of technologies via the fusion of technologies developed by the cooperative research among groups

Cooperative research plan

Inter-network

Key accomplishments

Activities

- <u>**Hosted symposia / workshops / conferences**</u>
  - "**Smart Submerged Floating Tunnel Systems Research Center**" in 4th International Conference on Computational Design in Engineering (**CODE2018**), Changwon, South Korea, April 1-5, 2018
  - "**KAIST ERC Special Session**" in **2018 Spring Conference**, Jeju, South Korea, April 5-7, 2018
  - **International Workshop on Smart SFTs**, and 1st Year Winter Workshop and 2nd Year Summer Workshop on Smart SFTs
  - "**1st China-Korea-Italy Workshop on SFTs**" in Hangzhou, China, October 12, 2018

- <u>**Invited seminars delivered by experts in the field of SFTs**</u>
  - "Global Dynamics Simulations of SFT (Submerged Floating Tunnel) including hydro-elasticity" by MH Kim (Professor, Texas A&M University), June 7, 2018
  - "Experiences, recent development, and ongoing research on Submerged Floating Tunnels in Norway" by Mathias Egeland Eidem (Project Manager, Norwegian Public Road Administration), January 29, 2018
  - "Innovations in infrastructure: Floating bridges" by Tina Vejrum (Vice President of Major Bridges International, COWI), January 29, 2018
  - "Global performance simulation of submerged floating tunnel by hydroelastic analysis" Heon Yong Kang (Research Assistant Professor, Texas A&M University), January 29, 2018

Research overview of Group I

Research Center for Smart Submerged Floating Tunnel Systems

KAIST
POSTECH
TEXAS A&M UNIVERSITY
KIOST
DAEWOO E&C
KICT KOREA INSTITUTE of CIVIL ENGINEERING and BUILDING TECHNOLOGY

Group I: Design•Analysis

- Analyzing global and local dynamic behavior under extreme and ocean environment loadings
- Design of anchorage-foundation system

KAIST TEXAS A&M UNIVERSITY KIOST 한국해양과학기술원

Group II: Materials•Construction

- Chloride-resistant material
- Self-healing concrete technology
- Integrated construction system
- Seabed-ground boundary construction

KAIST DAEWOO E&C

Group III: Monitoring•Maintenance

- Crack/ leakage detection
- Collision detection
- Robot system for maintenance
- Emergency evacuation technology

KAIST POSTECH KICT

Research overview of Group I

Group Member

[I-1 Team]

Park, Wooseon

KIOST

Research: Anchor system design

[I-2 Team]

Kwak, Hyo-Gyoung

KAIST

Research: Local static behavior analysis

[I-3 Team]

Kim, Dong-soo

KAIST

Research: Foundation-anchor system design

[I-4 Team]

Hong, Jung-Wuk

KAIST

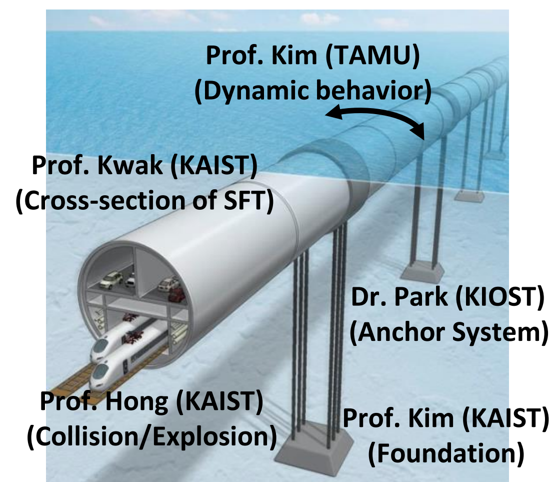
Research: Local dynamic behavior analysis

[I-5 Team]

Kim, Moohyun

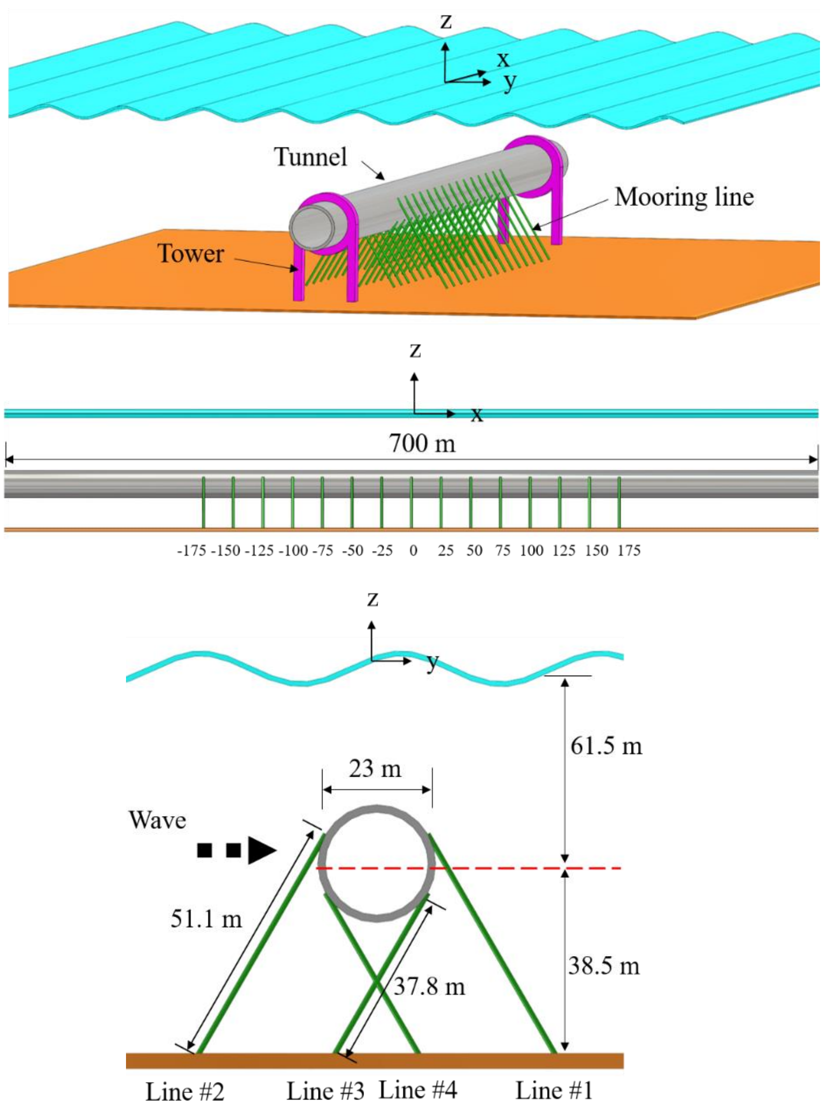
TEXAS A&M UNIVERSITY

Research: Global dynamic behavior analysis



[1] https://en.wikipedia.org/wiki/Submerged_floating_tunnel

Evaluation of global SFT behavior



2D and 3D schematic drawing of system

Major SFT parameters	Value	Unit
Tunnel		
Length	700 (varying)	m
Outer diameter	23	m
Bending stiffness	234.11×10^{11} (varying)	N-m²
Axial stiffness	4.27×10^{9} (varying)	N
Added mass coefficient	1.0	-
Drag coefficient	0.55	-
Mooring lines (Chain)		
Bar diameter	0.18	m
Installation span	25	m
Axial stiffness	2.77×10^{9}	N
Added mass coefficient	1.0	-
Drag coefficient	2.4	-

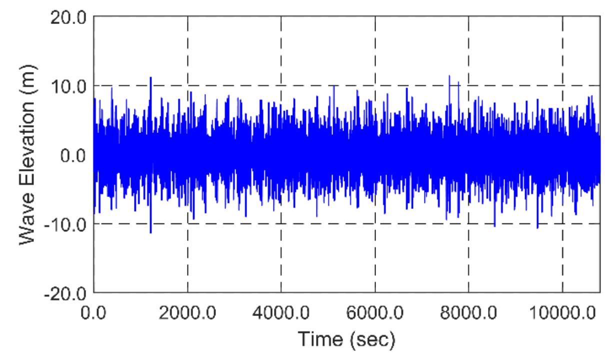
Component	Wet natural frequency (rad/s)	Mode number
Tunnel (Horizontal direction)	1.92	1st mode
	2.70	2nd mode
	4.53	3rd mode
Tunnel (Vertical direction)	3.12	1st mode
	3.45	2nd mode
	4.89	3rd mode
Mooring lines #1 and #2 (Center)	5.78	1st mode
Mooring lines #3 and #4 (Center)	9.04	1st mode

Evaluation of global SFT behavior

➢ Wave condition

- ✓ Wave elevation is produced by Jonswap wave spectrum.
- ✓ Wave force is acted at each node of the tunnel calculated by Morison Equation.
- ✓ Wave direction is perpendicular to the longitudinal direction of the tunnel

Significant wave height	Peak period	Enhancement parameter (γ)
11.7 m	13.0 sec	2.14



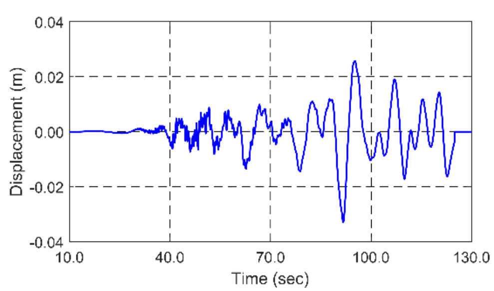
Time histories of wave elevation

* South sea of Korea 100-year typhoon condition

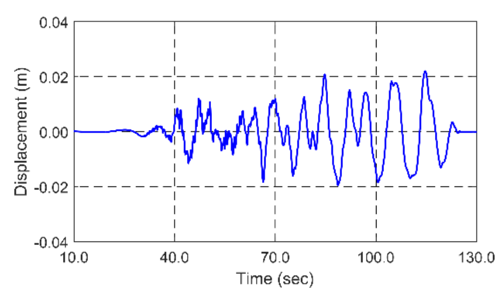
➢ Earthquake condition

Condition	Value
Richter Magnitude scale	6.8
Peak longitudinal motion (x) (cm)	-3.3
Peak transverse motion (y) (cm)	2.2
Peak vertical motion (z) (cm)	-1.7

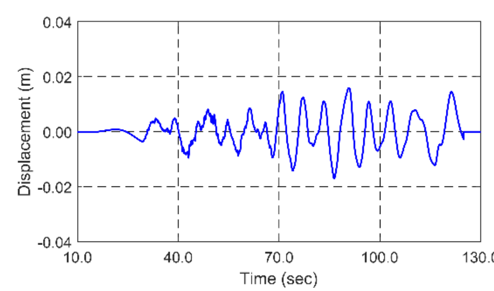
- ✓ Real seismic data (USGS: US Geological Survey)
- ✓ The earthquake occurred in 78 km WNW of Ferndale, California, USA in 2014.
- ✓ Seismic wave effects are considered by moving anchor location of mooring lines and both end locations of the tunnel at each time step.
- ✓ Based on seismic response spectrum of Korea, further research will be conducted.



Longitudinal seismic motion and spectrum



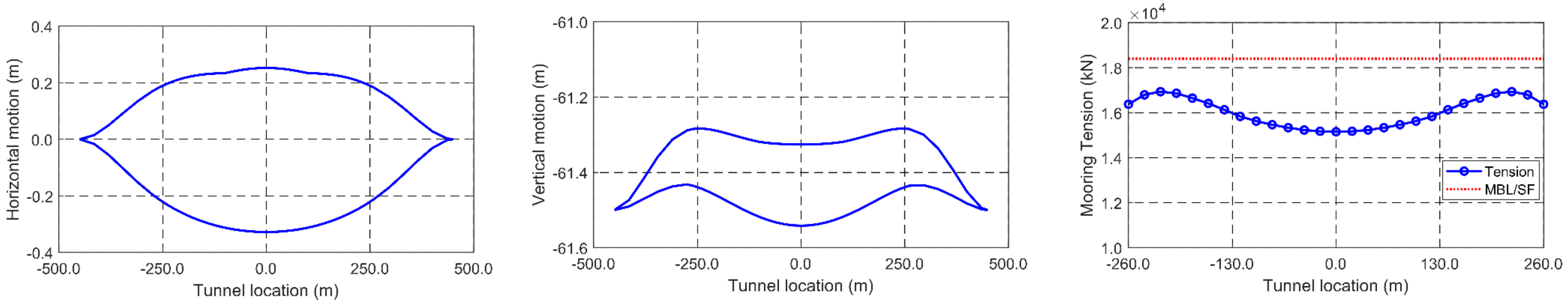
Transverse seismic motion and spectrum



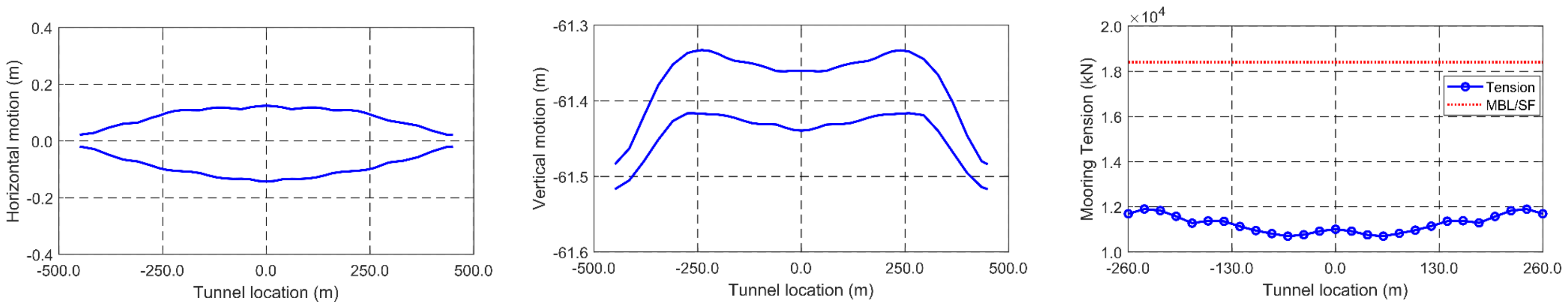
Vertical seismic motion and spectrum

Evaluation of global SFT behavior

- Results under wave excitations



- Results under seismic excitations



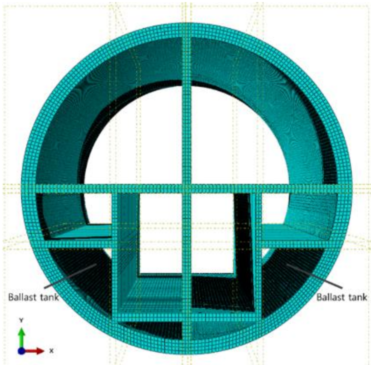
- What we found?
  - ✓ The 100-year-strom condition is more severe for global performance of the SFT.
  - ✓ Seismic excitations are also important since seismic-dominant-frequency ranges are close to tunnel's natural frequencies. In this case, tunnel's motions are larger than input seismic motion.
  - ✓ Mooring tensions are less than minimum breaking load with consideration for the safety factor of 1.67 (API criterion) under both wave and seismic excitations.

Local static analysis of SFT

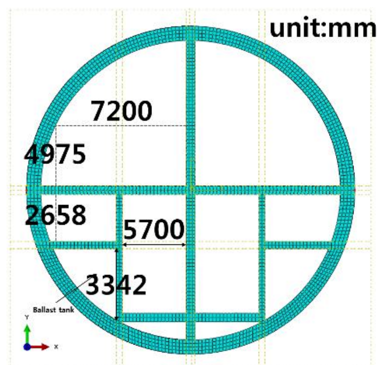
➢ Determination of Section Dimension

✓ Comparison of BWR affected by parameters & internal traffics

< Calculation of initial BWR with 23m & 20m diameter >



23m) Buoyancy: 4,173.4kN/m
Weight: 2,814.7kN/m
BWR=1.483



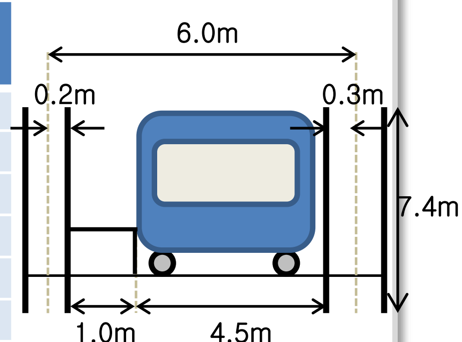
20m) Buoyancy: 3,155.7kN/m
Weight: 2,438.4kN/m
BWR=1.29

- According to the 'Highway & Railway design codes[1, 2]' in Korea, **minimum outer diameter** of SFT should be **20m** (4-way Road width 16m + outer,internal wall)
- Change of BWR by effect of **road traffic**(DB24, DL24 [1]) & **train load**(KRL-2012, [2]) was analyzed considering an influence line
- BWR affected by **a volume of ballast tank** have been calculated
(maximum 4.7% of total BWR)

< Change of BWR affected by internal traffics > **(D=23m)**

Road traffic (DL24)	Train traffic (KRL-2012)	Weight (kN/m)	BWR	BWR change (%)	Tension change (kN)	Tension (kN)
-	-	2,814.65	1.483	-	-	52,360
3	-	2,896.27	1.441	2.9	-719.7	51,640
-	1	3,045.45	1.370	8.2	-2,034.9	50,325
-	2	3,276.25	1.274	16.4	-4,069.8	48,290
3	1	3,127.08	1.335	11.1	-2,754.6	49,605
3	2	3,357.88	1.243	**19.3**	-4,789.5	47,571

< Calculation of 1-way railway dimension >

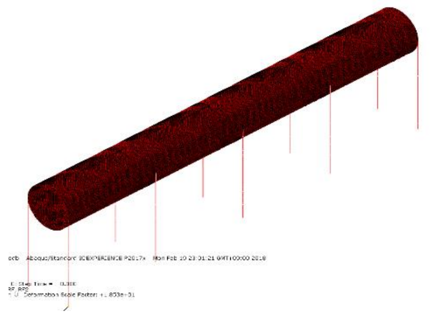


[1] Design standards for railway, Korea rail network authority (2011)
[2] Design standards for highway bridges (2012)

Local static analysis of SFT

- Mooring tension of SFT by 3D structural analysis

< Modeling of SFT tunnel and mooring lines >

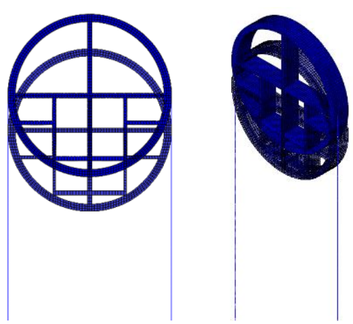


< Analysis result - displacement >

< Modeling details >

	Details
Sectional size	A 50,000mm long structural module of Funka bay tunnel * 4
Modeling element	tunnel – solid elem. Mooring line – beam elem.
Material properties	E_{conc}=30 GPa, $E_{mooring}$=108.85 Gpa
Etc.	Length of mooring line : 44.45m Fixed end condition

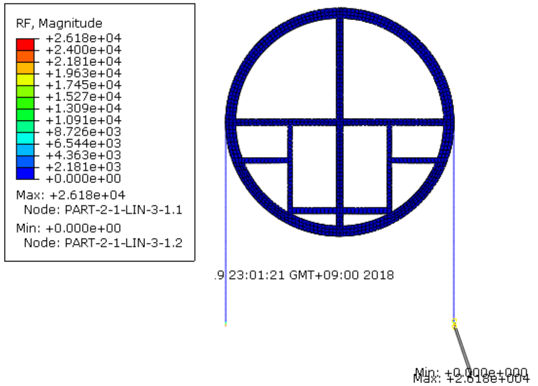
- Tensile force is generated at mooring line due to the buoyancy.
- Arch shaped stresses are observed as the displacement at the central part of the tunnel exceeds that at both ends.



[Cross section]

[Stress of the tunnel - Side view]

< Analysis result – reaction force >

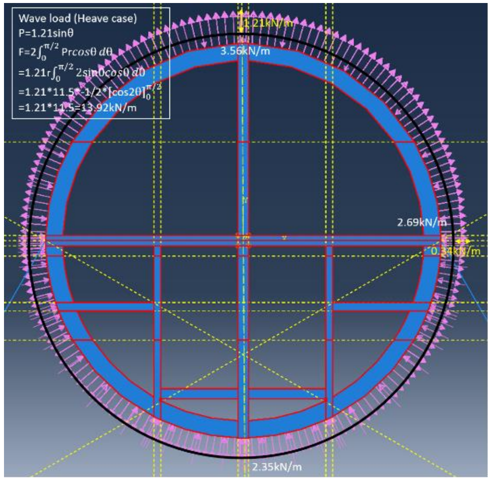


[Reaction force of the mooring line at the center]

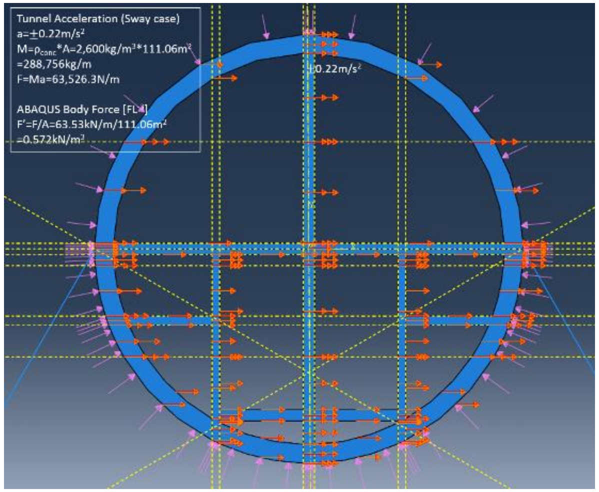
Local static analysis of SFT

➢ Effect of load combination on SFT by structural analysis

< Equivalent Wave Load >



< Equivalent Tunnel Acceleration>



< Mooring tensile reaction at center thru equivalent wave analysis >

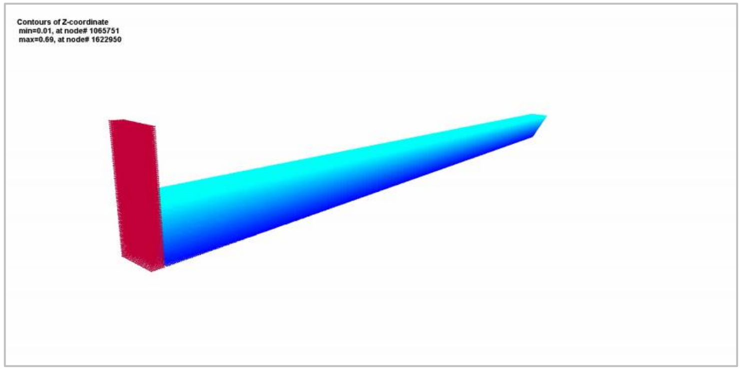
Position(z, m)	KAIST (kN)	TAMU (kN)	Error (%)
Static analysis	66,343.8	66,152.7	-0.29
+ Wave	73,502.52	71,893.25	-2.24
+ Added mass	80,902.52	77,753.05	-4.05
+ Damping	80,902.52	77,749.27	-
+ Inertia	88,305.62	91,195.4	3.17

- Equivalent static analyses for dynamic loadings are on going (vortex, earthquake, etc.)
- Validation with global analysis & theoretical results
- Determination of an optimum section through parametric study

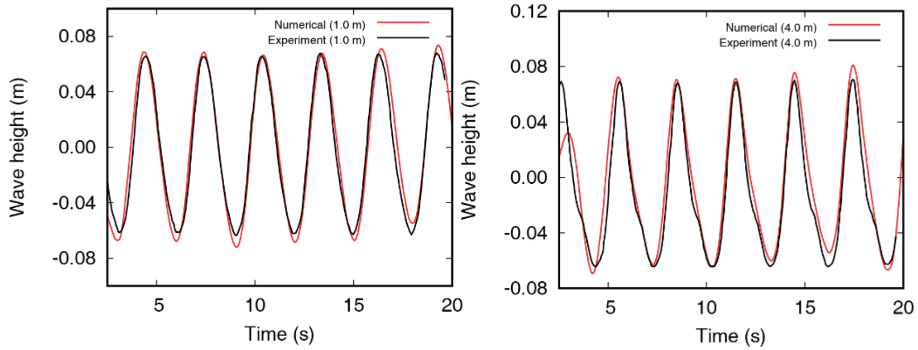
Local dynamic analysis of SFT

➢ Numerical wave flume

- **Wave modeling by using SPH method**

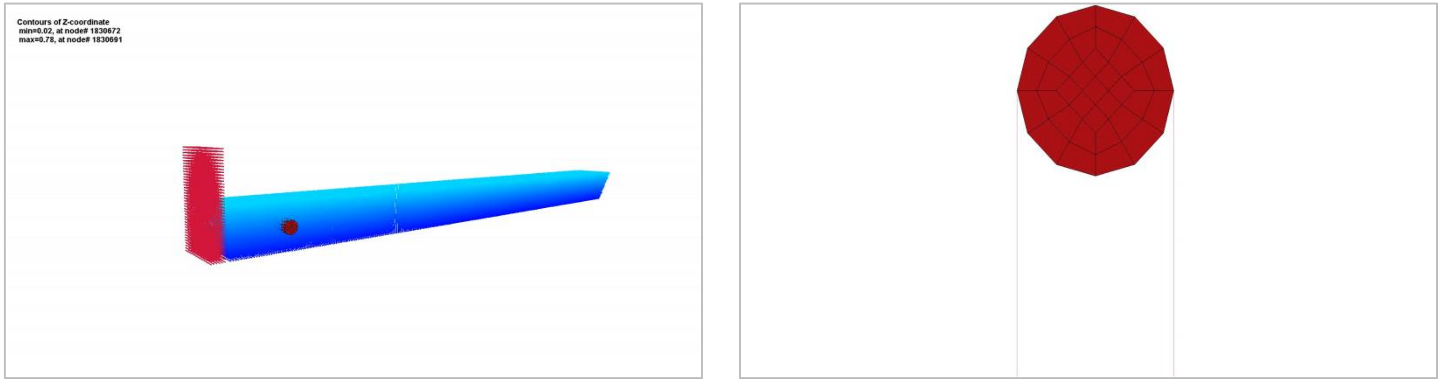


<Wavemaker simulation>



<Time series of surface elevation measured [3] and calculated at different positions in the flume>

- Smoothed particle hydrodynamics (SPH) is useful for expressing fluid flow and extreme deformation.
- Validation of numerical wave height is conducted through the comparison with experiment data [3].
- SPH method is used to model water, FE solid and truss element are used to model SFT and mooring.
- The interaction of the tunnel with the fluid is implemented using the contact algorithm.



<Fluid-Submerged floating tunnel interaction using FEM and SPH>

[3] Schäffer, H. A. (1996). Second-order wavemaker theory for irregular waves. *Ocean Engineering*, *23*(1), 47-88.

Underwater explosion (UNDEX) simulation

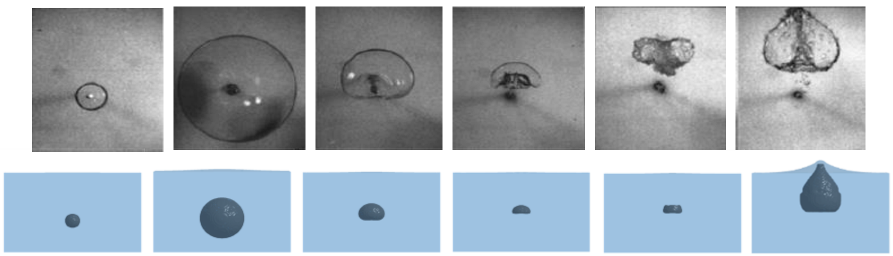
- **Evaluation of explosion load by using ALE method**

- In Arbitrary Lagrangian-Eulerian (ALE) description, nodes move in time as in Lagrangian algorithms or fixed in Eulerian[4].
- In order to rearrange the mesh, nodes move to an arbitrary point and consider relative motion of the material [4].
- Suitable for numerical analysis of high-speed deformation such as explosion pressure propagation.
- Validation of shock pressure and bubble phases was conducted through the comparison with empirical formula [4].
- It is possible to measure bubble pulse which can not be calculated by empirical formula [4].

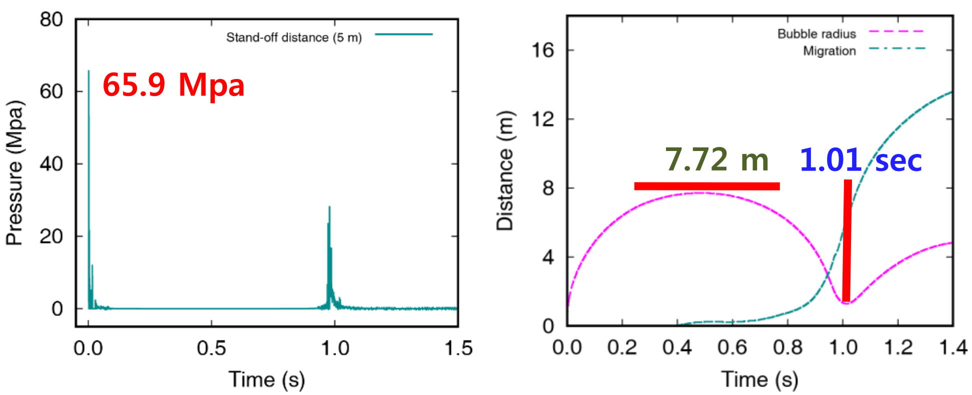
$$P_{max} = K_1\left(\frac{W^{1/3}}{R}\right)^{A_1} = 52.4 \times \left(\frac{200^{1/3}}{5}\right)^{1.18} = \mathbf{63.04\ Mpa}$$

$$T = K_5 \times \frac{W^{1/3}}{(D+10)^{5/6}} = 2.11 \times \frac{200^{1/3}}{(11+10)^{5/6}} = \mathbf{0.976\ sec}$$

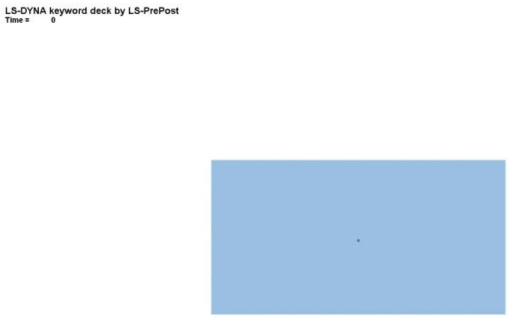
$$R_{max} = K_6 \times \frac{W^{1/3}}{(D+10)^{1/3}} = 3.50 \times \frac{200^{1/3}}{(11+10)^{1/3}} = \mathbf{7.42\ m}$$



<Comparison between analytical and numerical bubble phases [5]>



<Underwater explosion bubble phases and time history of pressure >



<UNDEX simulation (Video)>

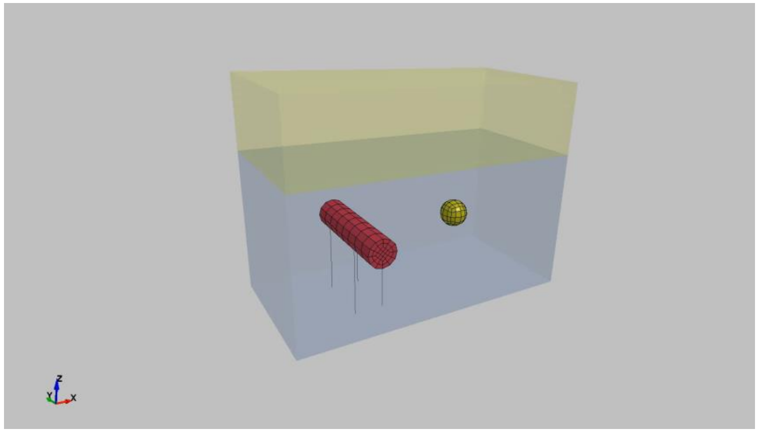
[4] Donea, J., & Huerta, A. (2003). *Finite element methods for flow problems*. John Wiley & Sons.

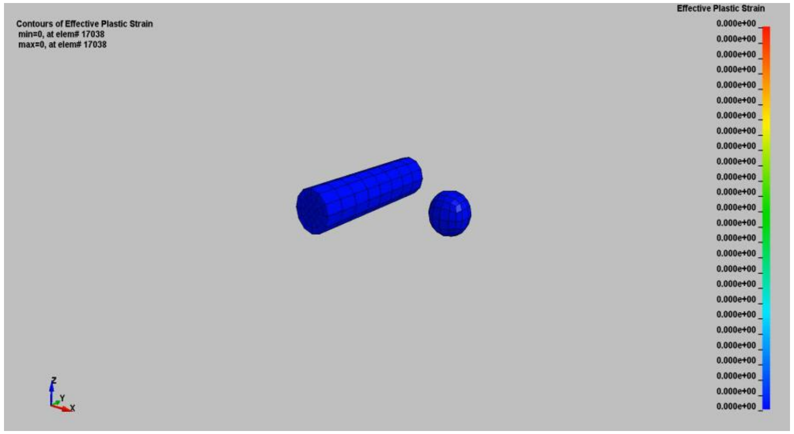
[5] Costanzo, F. A. (2011). Underwater explosion phenomena and shock physics. In *Structural Dynamics, Volume 3* (pp. 917-938). Springer, New York, NY.

Underwater collision simulation

- **Evaluation of impact force by using ALE method[6]**

- ALE method is used to model water and air, while FE solid element is used to model tunnel and impact body in the simulation.
- The interaction of the tunnel, impact body, and fluid is implemented using the contact algorithm.
- It is possible to analyze the external force applied to the tunnel according to the impact velocity of the impact body.





<Underwater collision simulation>

- **Future work**

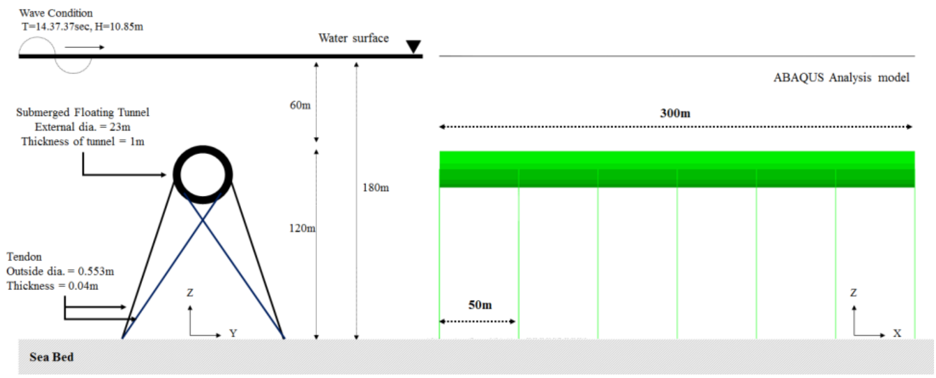
- The behavior of submerged floating tunnel against wave force, explosion pressure, and impact force will be analyzed.

[6] Swisdak Jr, M. M. (1978). *Explosion effects and properties. Part II. Explosion effects in water* (No. NSWC/WOL/TR-76-116). NAVAL SURFACE WEAPONS CENTER WHITE OAK LAB SILVER SPRING MD.

Design of anchor system

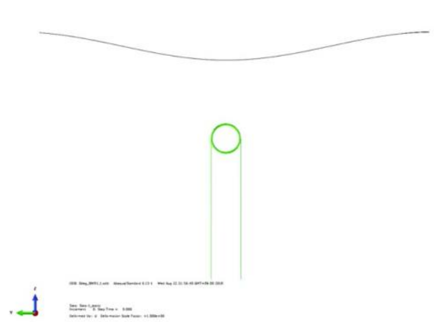
➢ **Hydrodynamic analysis for investigation of anchor system**

- **Anchorage system (ABAQUS modeling)**

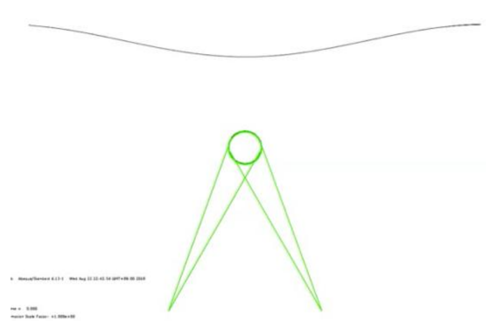


Hydrodynamic analysis for analysis of anchorage system(ABAQUS)

- **Dynamic response (Video)**



Type 1



Type 2

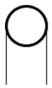
Parameters	Values
1. Environmental conditions	
Water depth (h, m)	180
Wave period (T, s)	14.37
Wave height (H, m)	10.85
2. Tunnel	
Outer diameter (m)	23
Wall thickness (m)	1
Elastic modulus (GPa)	30
Density (kg/m^3)	2400
Drag/added-mass coefficient	1.2/1.0
Clearance depth (m)	60
3. Hollow section of tether	
Outer diameter/thickness (m)	0.553/0.04
Elastic modulus (GPa)	210.0
Minimum yield stress (MPa)	482.6 (API X70)
Minimum ultimate stress (MPa)	565.4 (API X70)
Drag/added-mass coefficient	1.2/1.0
Tether spacing (m)	50.0

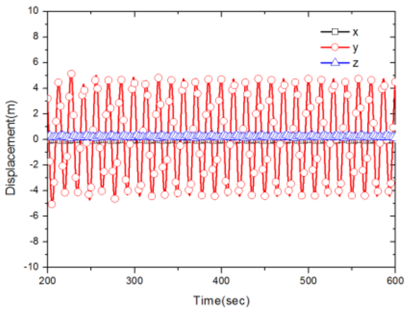
Design of anchor system

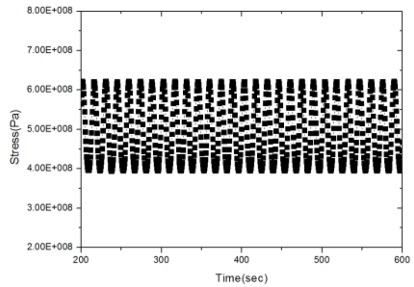
➢ **Hydrodynamic analysis for investigation of anchor system**

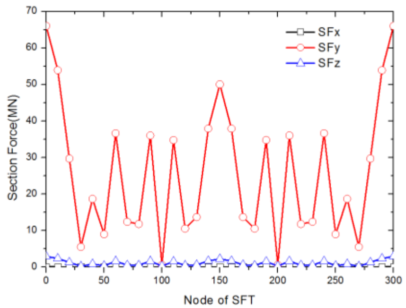
	Displacement of tunnel	Stress of tether	Absolute maximum **section force** at each point of SFT	Absolute maximum **section moment** at each point of SFT

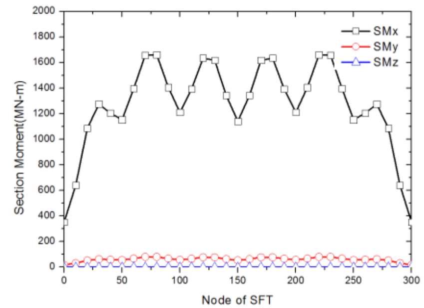
Type 1





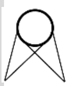


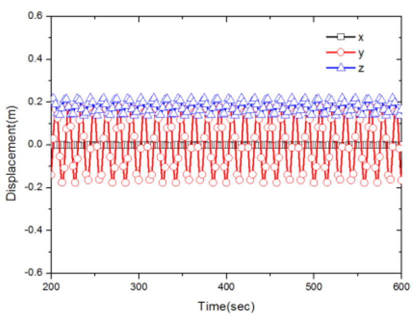


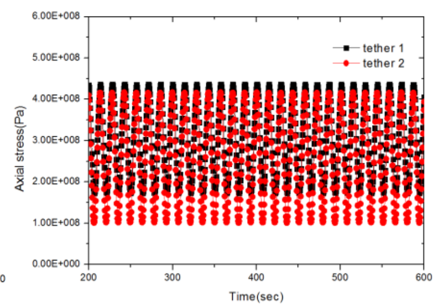


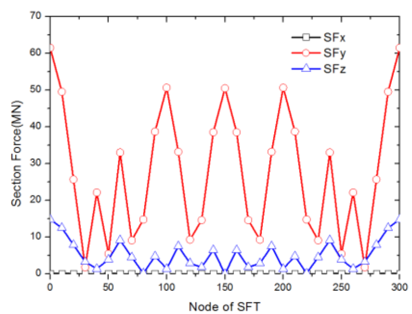
Max. displ.=5m | Max. Stress=640MPa | ABS. Max. SF=50MN | SMx = 1600MN-m

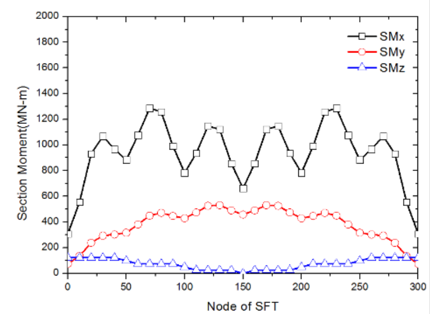
Type 2











Max. displ.=0.22m | Max. Stress=450MPa | ABS. Max. SF=50MN | SMx = 1300MN-m

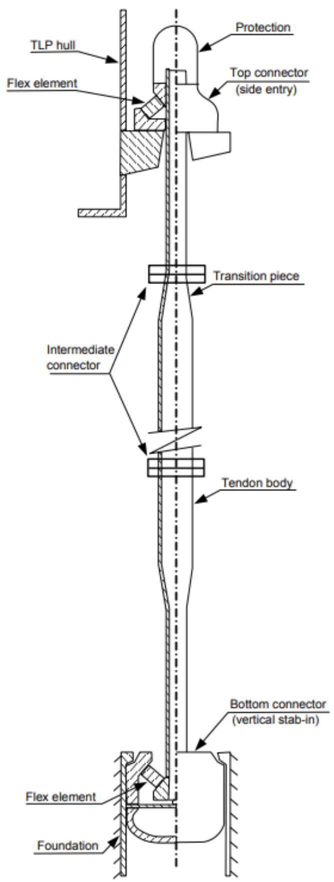
Design of anchor system

➢ Design and analysis of padeye (between tension leg and foundation)

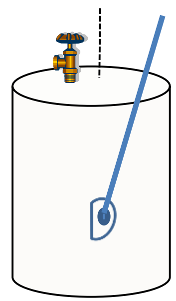
- Development of design sheet for padeye refer to DNV 2.7-1,3 and AISC code
- Verification of proposed design sheet using FE analysis

◀ **Suggestion of joint part between tunnel and tension leg refer to DNV code**

▼ **Joint part between tension leg and foundation**

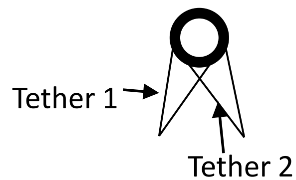


TLP tendon system
(cf DNV-OS-C105[7]')

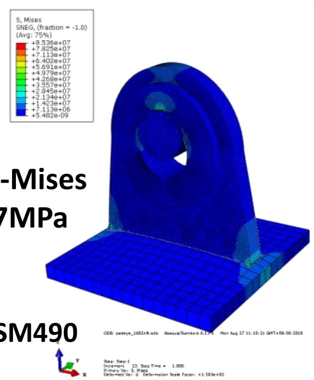


Suction anchor

BWR 1.2	tether1	tether2
Type 1	2.4 MN	
Type 2	12.8 MN	17.1 MN



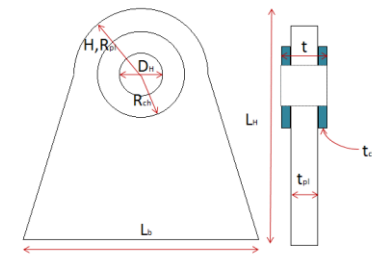
Max. Von-Mises stress 87MPa



Steel type SM490

Analysis of padeye

Design sheet for padeye



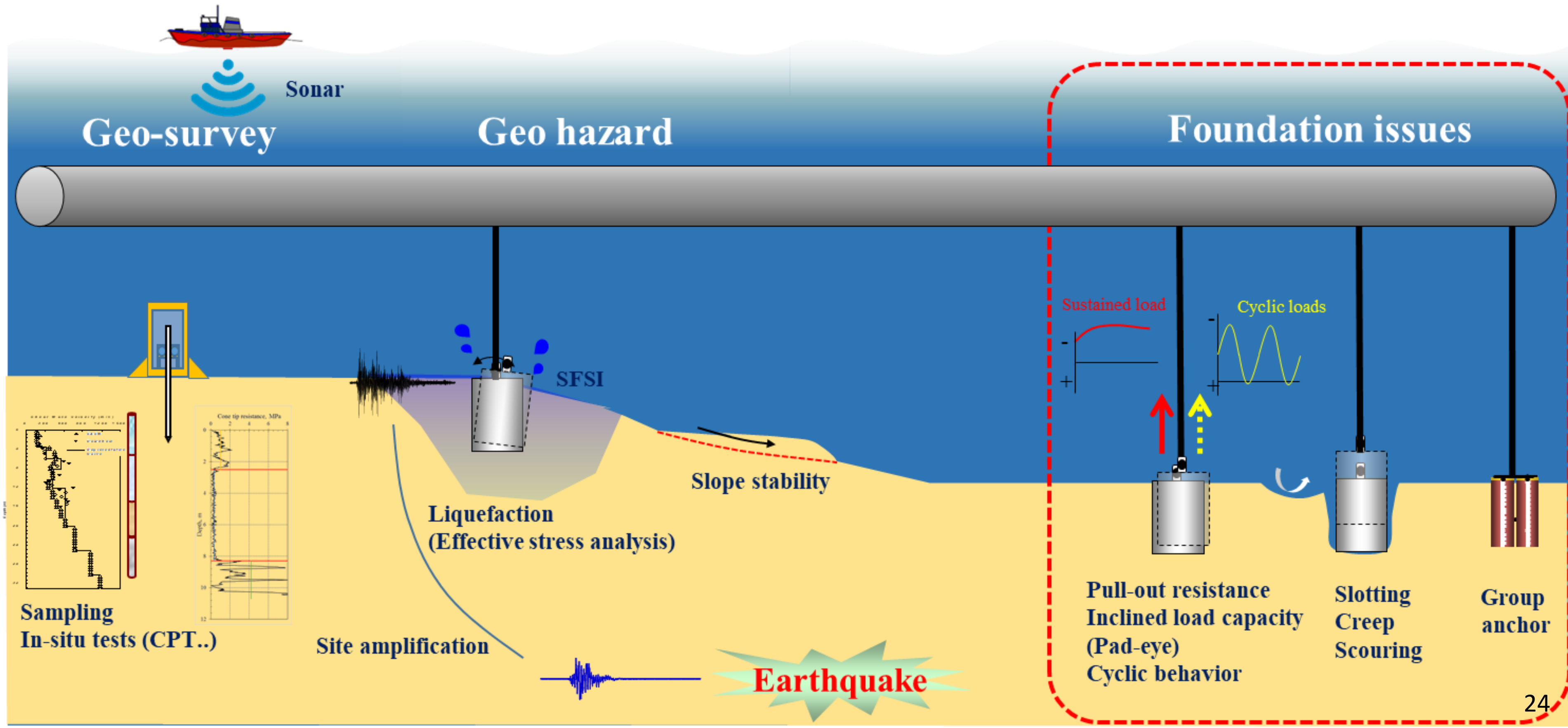
Geometric properties

Design load (F) =	1,700,000N
Thickness of padeye(t) =	160mm
Thickness of padeye plate(t_{pl}) =	80mm
Thickness of cheek plates(t_{ch}) =	40mm
Diameter of pinhole(D_H) =	240mm
Radius of cheek plate(R_{ch}) =	240mm
Diameter of cheek plate(D_{ch})	480mm
min. distance from centre hole to edge of plate(H, R_{pl}) =	300mm
Diameter of shackle pin(D_{pin}) =	200.00mm
Thickness of suction anchor =	60.00mm
Sling set(EA) =	1
Angle between sling leg vertical	0
Weld throat thickness for padeye(mm)	56.56mm
length of bottom for padeye(L_b)	720.0mm
Height of padeye(L_H)	720.0mm

[7] DNV-OS-C105 structural design of TLPS

Foundation-anchor system design

- Geotechnical Issues
  - ✓ High target safety level
    - ✓ Small allowable displacement (Tunnel allowable displacement for plastic ground: 20~40mm)
  - ✓ Unique loading characteristics
    - ✓ Huge sustained pullout loading (Buoyancy) + Cyclic loading (Wave)
  - ✓ In this study, focus is on foundation issues in sand



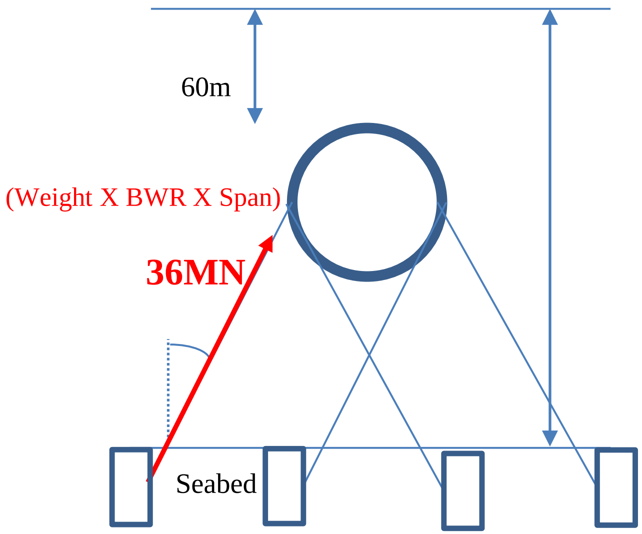
Analytical calculation of anchor capacity

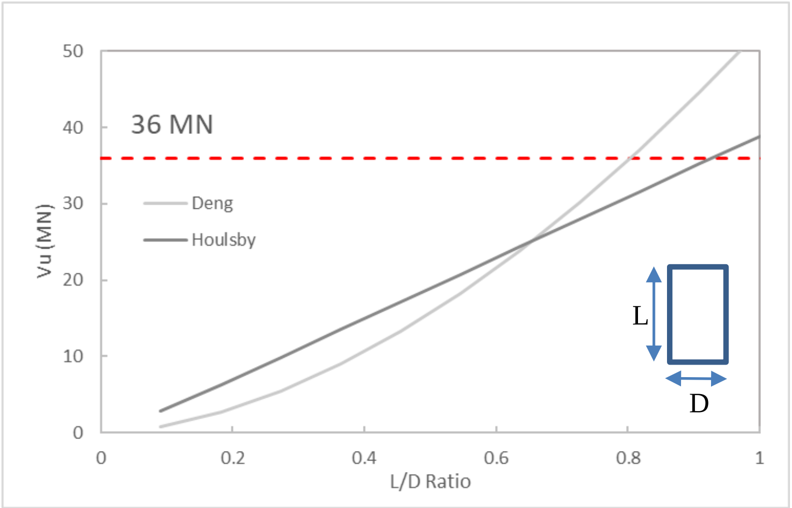
- Design of suction anchor specification
  - Applied Pull-out estimation

    = Weight x BWR x Span

    = Target load per each suction bucket : **36MN**
  - Design the suction anchor dimension
    - Find D x L using Deng equation [8]
    - Find D x L using Houlsby equation [9]
  - Final size D x L : **11 x 11 or 11 x 9** for suction anchor
    - ✓ Verified by ABAQUS

Available options			
Eq. by Deng [8]		Eq. by Houlsby [9]	
Diameter (m)	Length (m)	Diameter (m)	Length (m)
10	10	11	11
11	9	12	9
9	11	10.5	12





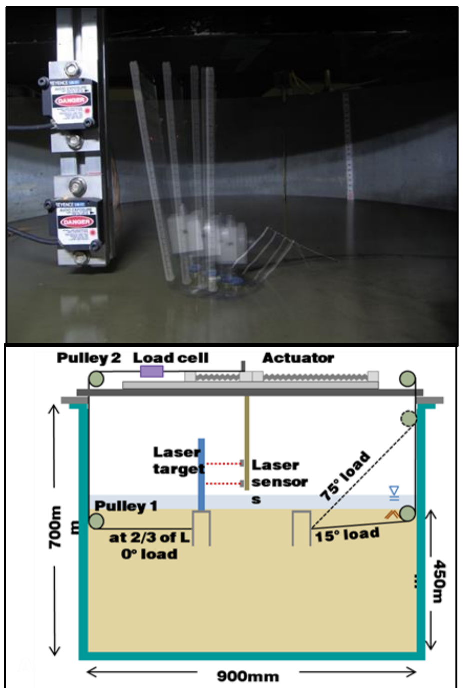
Ultimate capacity with bucket size

[8] W. Deng and J. P. Carter , A Theoretical Study of the Vertical Uplift Capacity of Suction Caissons, International Journal of Offshore and Polar engineering, Vol. 12, No. 2, June 2002 (ISSN 1053-5381)

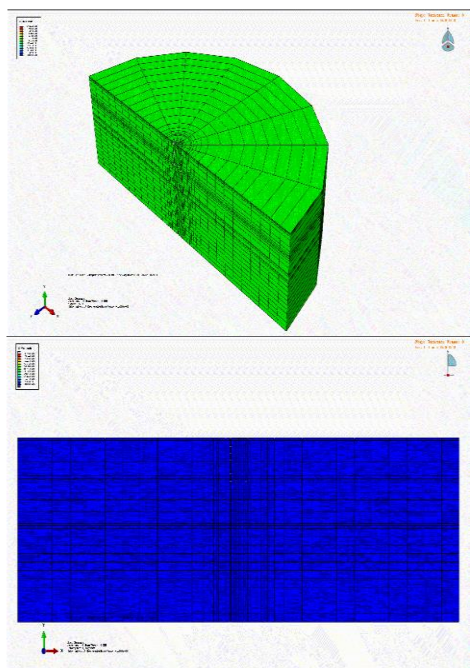
[9] Houlsby, Guy T., Richard B. Kelly, and Byron W. Byrne. "The tensile capacity of suction caissons in sand under rapid loading." Proceedings of the international symposium on frontiers in offshore geomechanics, Perth. 2005.

Evaluation of the suction anchor - static

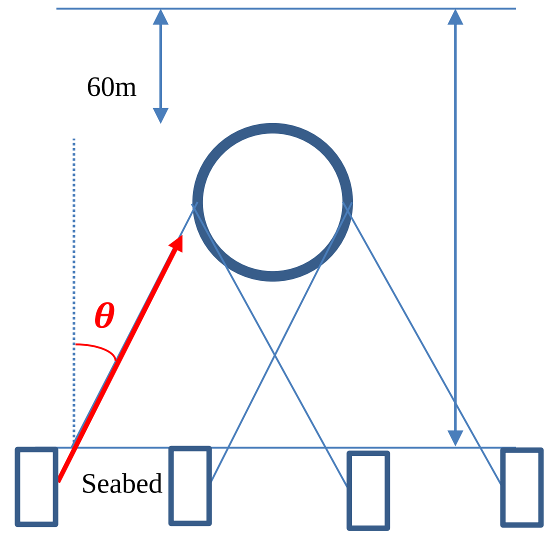
- Behavior of the suction anchor
  - Undersea loading condition : Lateral component + Vertical component
    - Need to estimate the effect of the inclined load
  - Seafloor condition : Irregular soil along the tunnel longitudinal direction
    - Need to estimate the effect of the soil properties
    - Conducting the numerical analysis
    - Verifying data using centrifuge
  - **A Numerical study study for horizontal loading**
    - Parameter : Soil elastic modulus / Friction angle / Inclined load

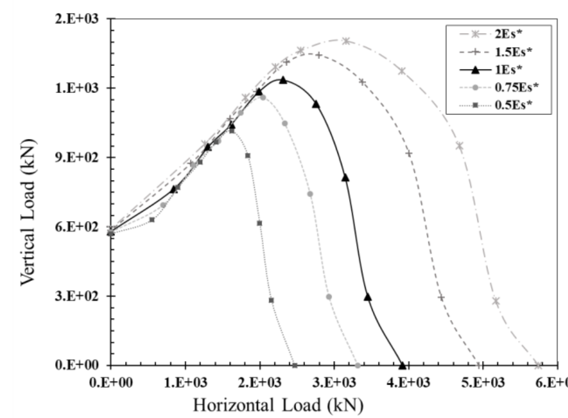


[Centrifuge model tests]



[Numerical test]



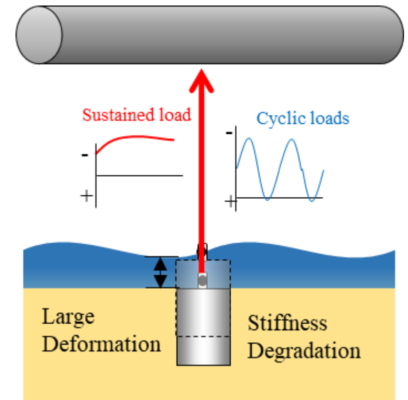


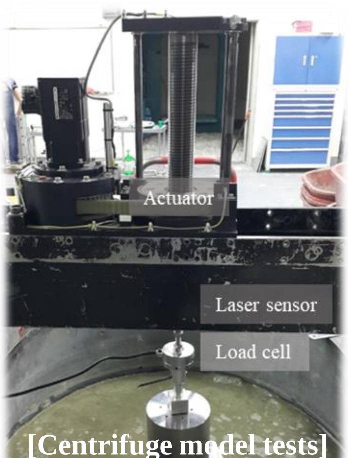
[Failure envelope]

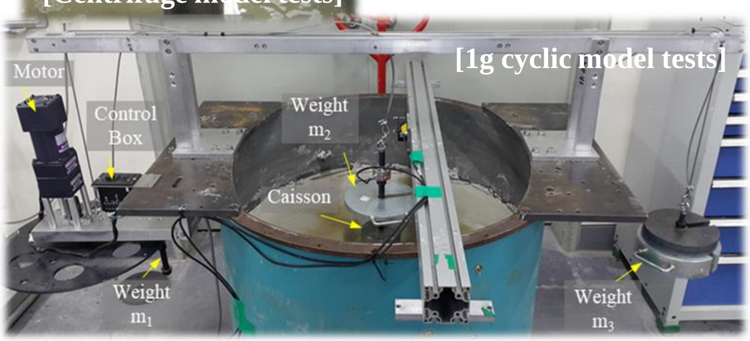
: Simultaneously express the horizontal and vertical failure load according to angle.

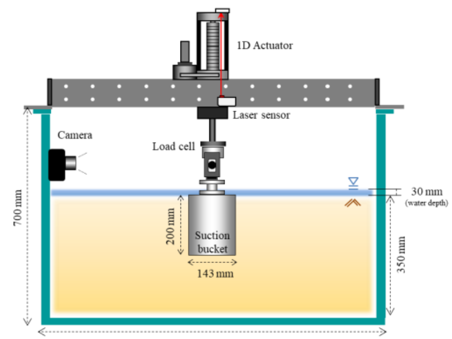
Evaluation of the suction anchor - cyclic

- Cyclic behavior of the suction foundation
  - Undersea loading condition : **Sustained buoyancy + Cyclic loading**
    - Need to estimate the effect of cyclic loading considering the buoyancy
  - Using centrifuge & 1g small scaled model tests
    - Permanent displacement / Stiffness variance
  - **Parametric study for cyclic loading**
    - Parameter : Loading level → P-1 / P-2 (FLS /SLS, 30 % / 50% of Ultimate Limit State)

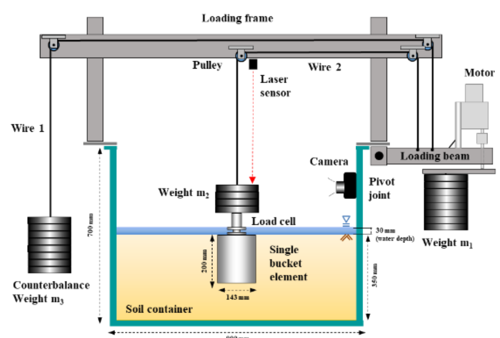




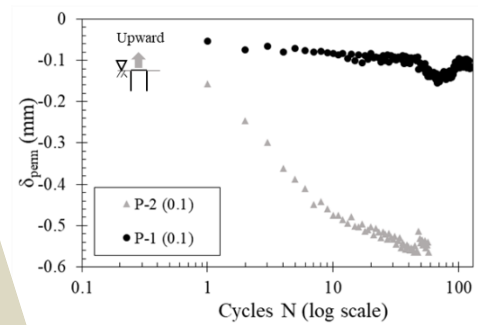




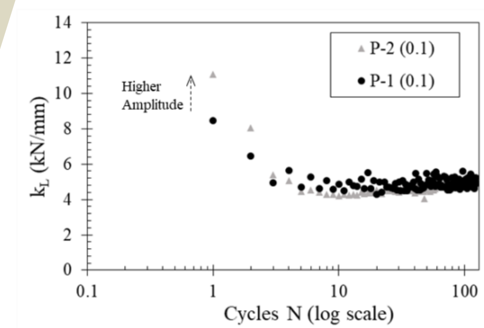
[Centrifuge model tests]



[1g cyclic model tests]



[Permanent Deformation]



[Stiffness variance]

Research overview of Group II

Research Center for Smart Submerged Floating Tunnel Systems

KAIST, POSTECH, TEXAS A&M UNIVERSITY, KIOST, DAEWOO E&C, KICT (KOREA INSTITUTE of CIVIL ENGINEERING and BUILDING TECHNOLOGY)

Group I: Design•Analysis

- Analyzing global and local dynamic behavior under extreme and ocean environment loadings
- Design of anchorage-foundation system

KAIST, TEXAS A&M UNIVERSITY, KIOST 한국해양과학기술원

Group II: Materials•Construction

- Chloride-resistant material
- Self-healing concrete technology
- Integrated construction system
- Seabed-ground boundary construction

KAIST, DAEWOO E&C

Group III: Monitoring•Maintenance

- Crack/ leakage detection
- Collision detection
- Robot system for maintenance
- Emergency evacuation technology

KAIST, POSTECH, KICT

Research overview of Group II

Group Member

[II-1 Team]

Lee,
Haengki

KAIST

Research: Development of highly-durable concrete for SFTs

[II-2 Team]

Kim,
Jechun

DAEWOO E&C

Research: Development of integrated construction system for smart SFTs

[II-3 Team]

Cho,
Gyechun

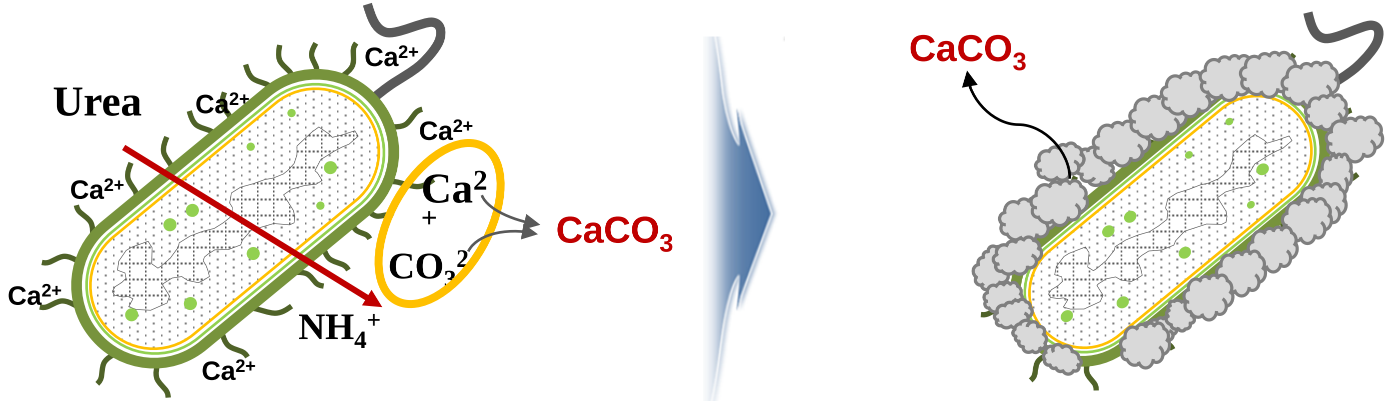
KAIST

Research: Boundary between subsea bored tunnel and floating tunnel

Self-healing concrete

Self-healing concrete using biomineralization

- The formation of micro-cracks in underwater concrete structures
  - ✓ The **micro-cracks** are caused by external force and shrinkage, and make the transport of moisture and chemicals through a matrix, **accelerating concrete deterioration**[10].
  - ✓ Repair work is necessary to extend the service life of concrete structures.
- Self-healing concrete using biomineralization
  - ✓ The **biomineralization** is a feasible method for self-healing micro-cracks, by **filling $CaCO_3$ in cracks and pores of concrete using ureolytic bacteria** [11].



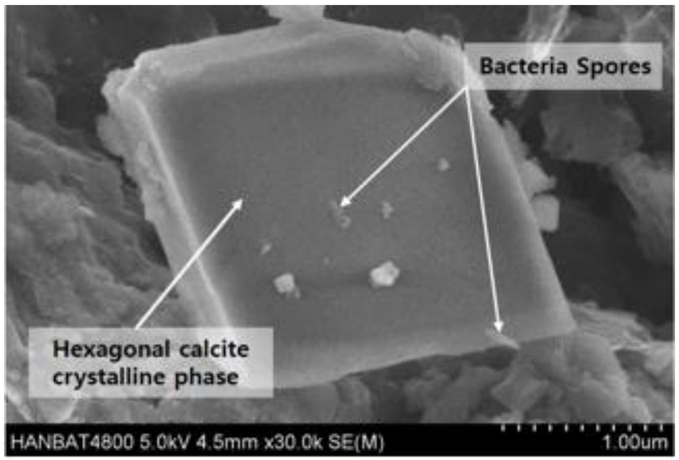
<Ureolytic bacteria>

<$CaCO_3$: material as a filler for cracks and pores in concrete>

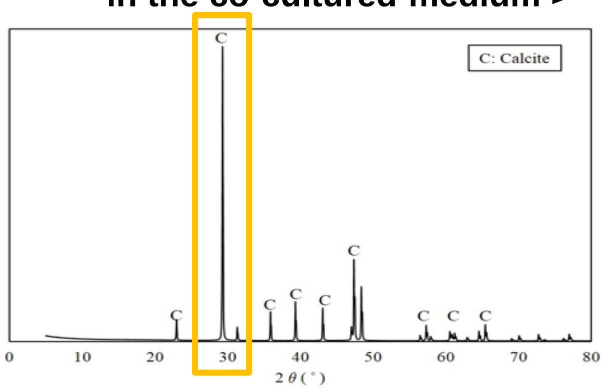
[10] S, A. Altoubat and D, A. Lange. (2001). Creep, shrinkage and cracking of restrained concrete at early age, ACI Materials Journal, Vol. 98, pp. 323-331.
[11] Jonkers, H. M., Thijssen, A., Muyzer, G., Copuroglu, O., & Schlangen, E. (2010). Application of bacteria as self-healing agent for the development of sustainable concrete. Ecological Engineering, Vol. 36, pp. 230-235.

Self-healing with co-cultured bacteria[10-1]

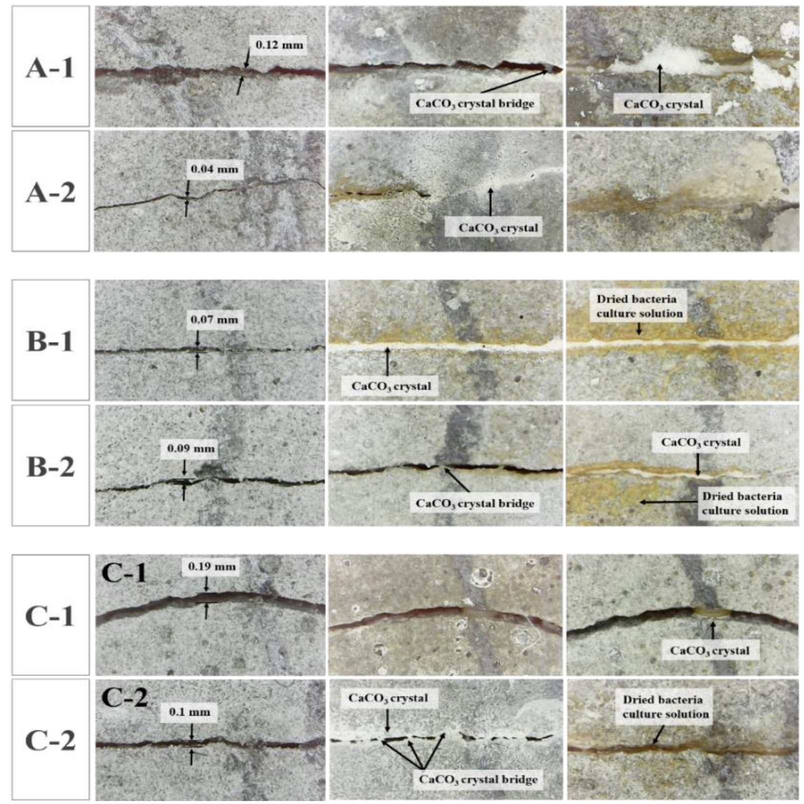
- The urea-calcium lactate medium was co-cultured. Faster growth rate of the non-ureolytic bacteria *B.thuringiensis* provides larger nucleation site which leads to enhanced $CaCO_3$ precipitation.



<SEM images of calcite precipitation in the co-cultured medium >



<XRD pattern of dry weight of precipitated $CaCO_3$ at urea-calcium lactate medium>



<Microscopic observation of crack healing after 1 and 3 days of incubation>

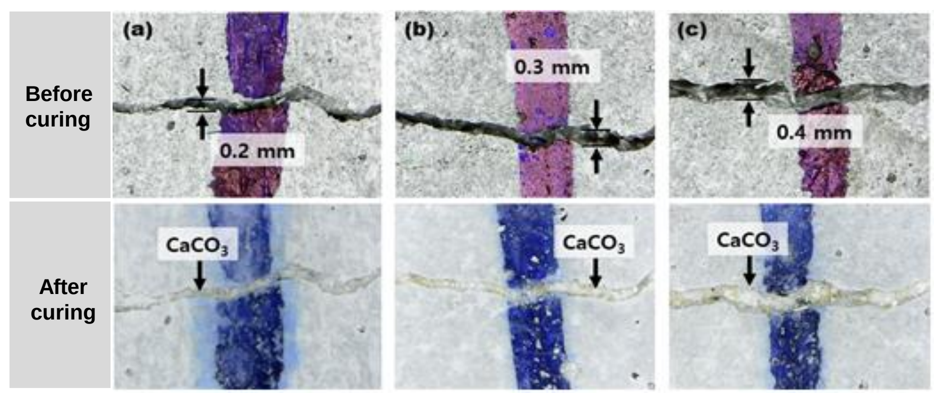
[10-1] H.M. Son, H.Y. Kim and H.K. Lee, (2018) *Materials*, 11(5), pp. 782.

Self-healing concrete

Isolation of marine bacteria

- Marine environments accelerate the chloride penetration, hence it is more difficult to repair concrete micro-cracks in a marine rather than a soil environment[12].
- We proposed **ureolytic marine bacteria isolation** that would effectively precipitate $CaCO_3$ in a marine environment.
- Bacteria ***Marinomonas pontica*** isolated from domestic sea water was found to precipitate calcium carbonate through urea degradation and calcium consumption, and was effective to repair cracks in concrete.

<Sampling and Single colony selection>



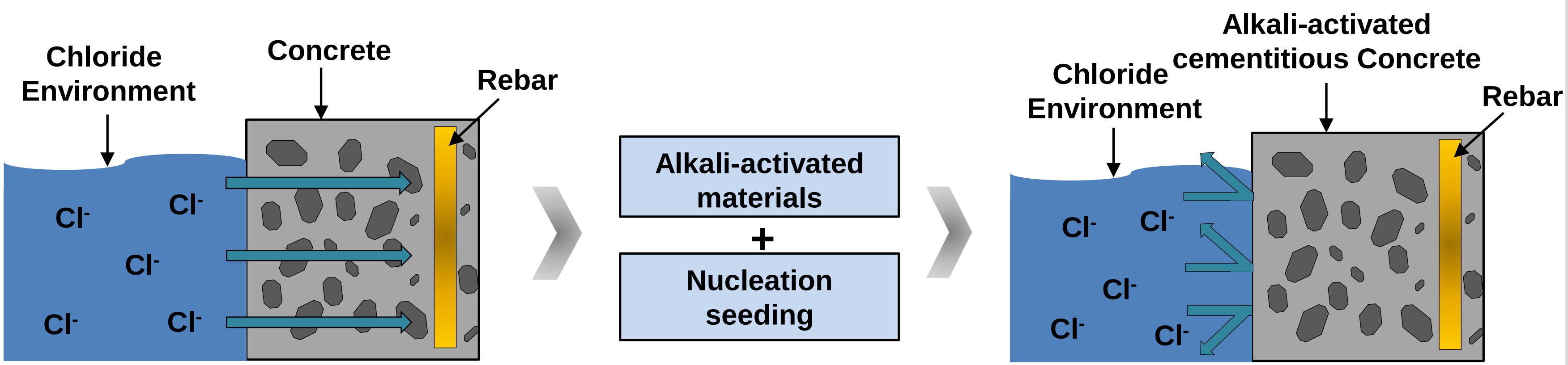
<Microscopic observation of crack healing by $CaCO_3$ formed by bacteria>

[12] M.H.P. Kadam, D.B. Desai and A. K. Gupta (2017). Repairing and strengthening techniques for historic masonry arch bridges, Imperial Journal of Interdisciplinary Research, Vol. 3, pp. 1172-1176

Concrete with high chloride resistance

Chloride ingress in concrete structures

- Chloride ions react with the passivation layer of rebar embedded in concrete and cause corrosion of the rebar, leading surface cracking and spalling of the concrete.
- Highly durable cementitious materials with **high chloride penetration resistance are required for marine structures** including submerged floating tunnel systems[13].
- Using **alkali-activated materials (i.e., fly ash, blast furnace slag) and nucleation-seeding** to develop highly durable materials with high chloride resistance.



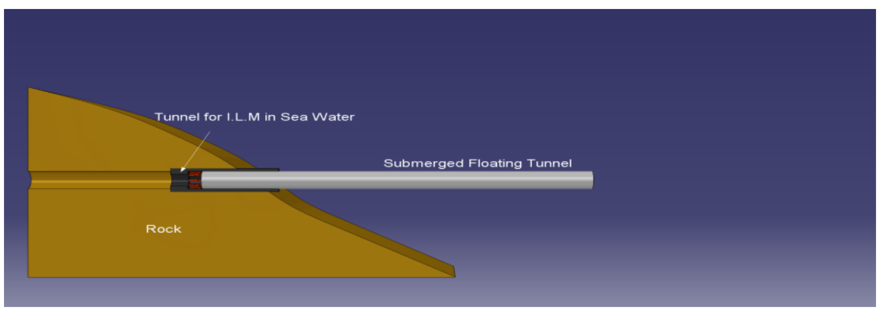
<Schematics of highly durable materials development>

[13] A. Neville, Chloride attack of reinforced concrete: an overview, Mater. Struct. 28 (1995) 63.

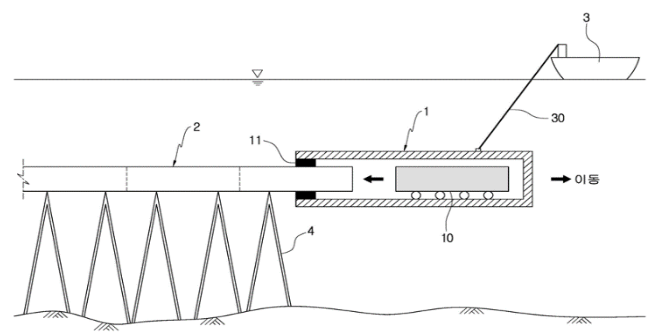
SFT construction method development

Developing new construction concepts for SFT continuations

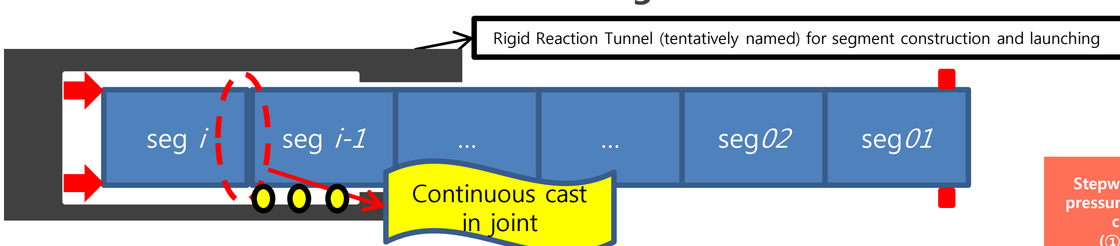
- SFT construction concepts
  - ✓ Methods for constructing submerged tunnels are being studied.
  - ✓ Long, straight portion of SFT constructed under the balance of buoyancy and dead load with the minimum extrusion force ➔ **Underwater ILM**
  - ✓ Long, straight or curved portion of SFT construction by **using dry-dock** are considered.
  - ✓ **New extended immersed tunnel construction utilizing a moving dry dock is being conceptually investigated**.

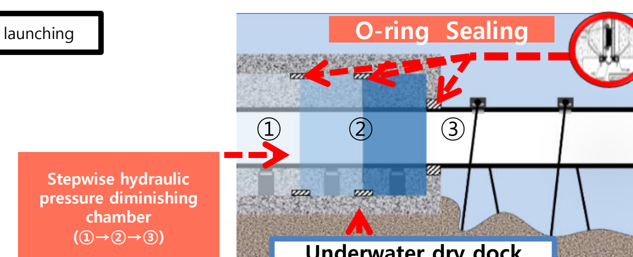


Underwater Incremental Launching Method



Moving Dry-Dock Method

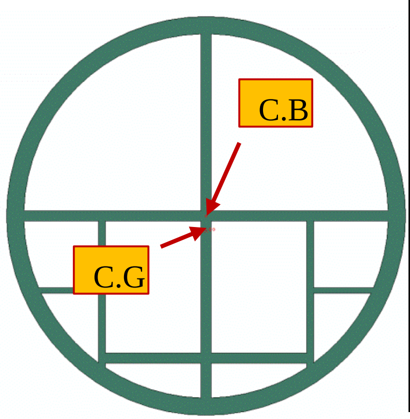




SFT module optimization in production/transportation/installation

Investigation of various SFT module sections

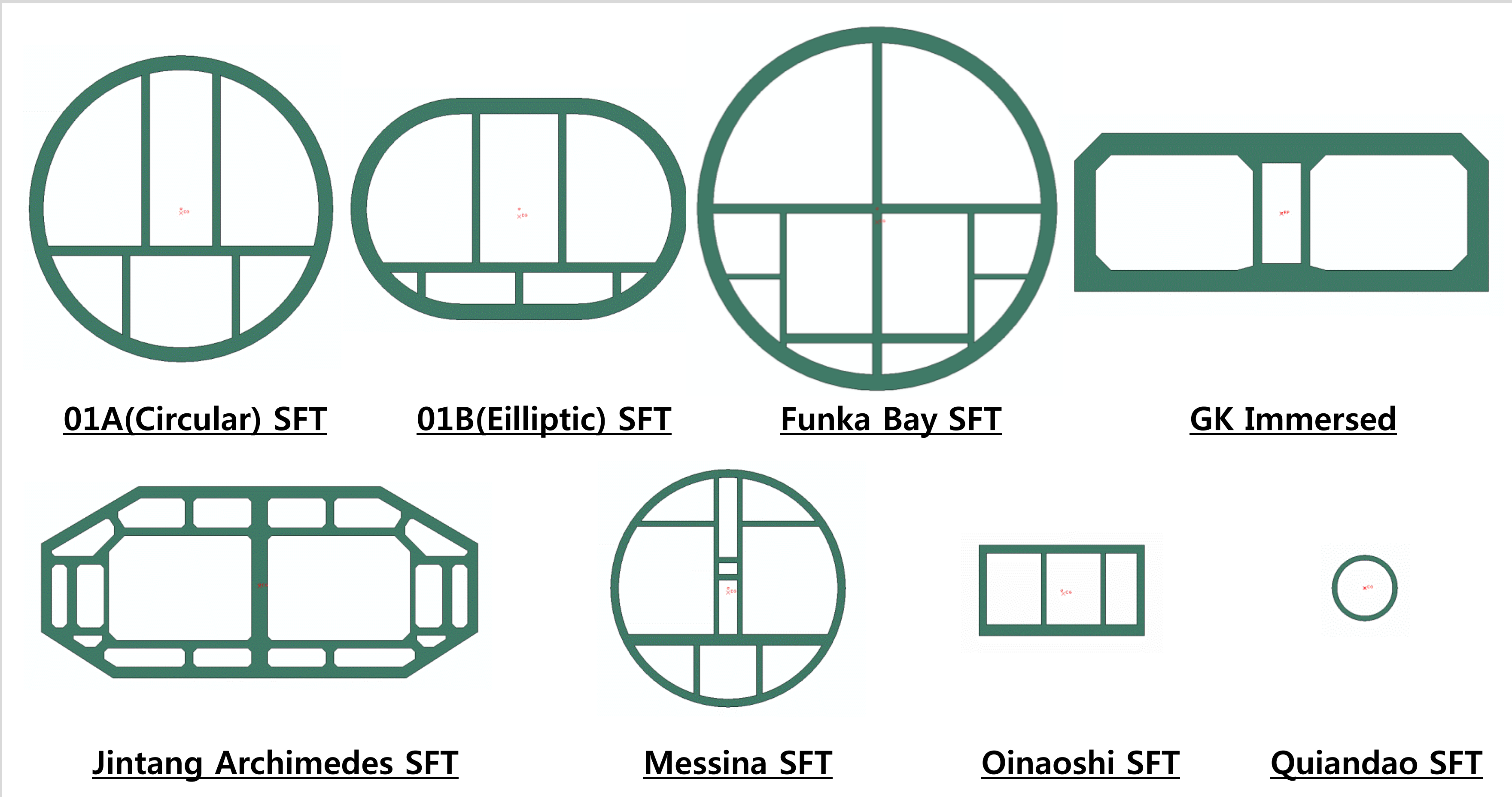
- To check mooring line of various SFT module under construction condition
  - ✓ Various SFT sections proposed by many researchers are investigated.
  - ✓ Under the condition of SFT module in transportation or mooring, the responses of SFT module and forces in tethering are computed.
  - ✓ ABAQUS/AQUA using beam models is used in computation.
  - ✓ Sectional constants such as Ixx, Iyy and A are calculated from the geometry of SFT section.
  - ✓ The stabilities in immersing SFT module will be checked in considering the ballast water.
  - ✓ More rigorous approaches considering wave diffractions are on going.



Section	weight (tonf)	buyancy (tonf)	C.G		C.B		I_{xx} (m^4)	I_{xx} (m^4)	A (m^2)
			X	Y	X	Y			
01A	191.954	295.572	0.000	-0.275	0.000	0.000	2691.075	2597.184	78.349
01B	190.740	258.917	0.000	-0.478	0.000	0.000	1785.537	3153.727	77.853
Funka	267.614	415.455	0.000	-0.847	0.000	0.000	5305.785	5099.369	109.230
GK	248.415	260.813	0.000	-0.084	-0.051	0.000	1460.055	7017.892	101.394
Jintang	243.578	301.906	0.000	0.115	0.000	0.219	1612.046	6901.852	99.420
Messina	108.627	176.694	0.000	-0.277	0.000	0.000	889.541	766.342	44.338
Oinaoshi	48.804	60.420	1.252	-0.353	1.150	-0.150	96.613	276.361	19.920
Quiandao	8.876	13.505	0.000	0.000	0.000	0.000	6.761	6.761	3.623

SFT module optimization in production/transportation/installation

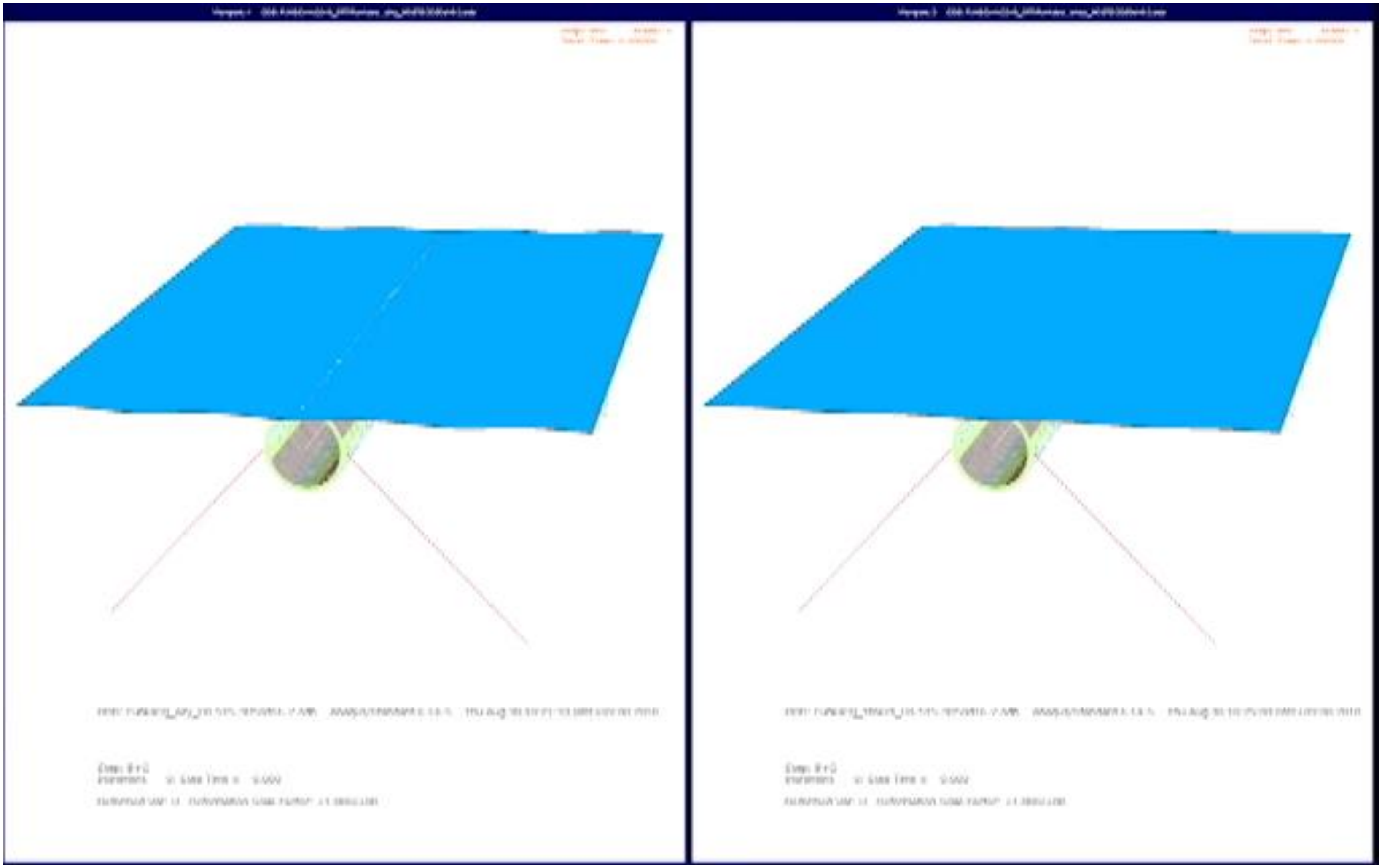
Center of gravity (C.G) and center of buoyancy (C.B) of proposed SFT sections (cf. [16-23])



[16] MARTIRE, Giulio. The Development of Submerged Floating Tunnels as an innovative solution for waterway crossings. 2010. Ph. D Thesis. Università degli Studi di Napoli Federico II.
[17] https://www.weforum.org/agenda/2016/07/norway-could-build-the-worlds-first-floating-tunnel.
[18] 박우선, 한상훈, 오상호, 고진환, 한택희, 이진학, 박영현, 정원무, 오영민, 신창주, 안희도, 이달수, 채장원, 원덕희, 이상현, 백승미, 서지혜, 지창환, 이성봉 외 3명, 해중터널 실용화를 위한 핵심기술 개발 (1단계), 한국해양과학기술원 (2013).
[19] Shunji Kanie, Feasibility on various SFT in Japan and their technological evaluation. Procedia Engineering 4 (2010) 13-20.
[20] First International Symposium on Archimedes Bridge (ISAB-2010), Procedia Engineering, Vol. 4.
[21] 수중터널연구조사회 '일본 수중터널 보고서', 1995.
[22] XIANG, Yiqiang, et al. Risk analysis and management of submerged floating tunnel and its application. Procedia Engineering, 2010, 4: 107-116.
[23] Mazzolani, F. M., Landolfo, R., Faggiano, B., Esposto, M., Perotti, F., & Barbella, G. (2008). Structural analyses of the submerged floating tunnel prototype in Qiandao Lake (PR of China). Advances in structural engineering, 11(4), 439-454.

SFT module optimization in production/transportation/installation

Structural checks for mooring line of Funka Bay SFT (Hs=0.5m, T=5.3sec, Vy=1m/s)



Consideration on boundary connecting module

Boundary connecting modules

- Six degree-of-freedom analysis on the boundary connecting module
  - ✓ As the ocean environmental loads (wave, tidal, tsunami, etc.) occurred, the **stress concentration** would occur **on boundary** between subsea bored tunnel (relatively fixed behavior) and floating tunnel (relatively free behavior).
  - ✓ The **six degree-of-freedom free design** of connecting module **is required** to minimize the impact of oceanic dynamic loads[24].

- **Hinged connection** shows only about 50% of rigid connection.
- **Elasto-plastic bearing** shows transverse shear force 18.9% less and transverse moment 49.1% less than that of hinged connection.

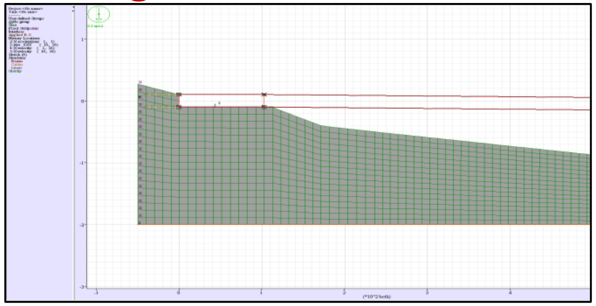
- The boundary connecting module should be **hinged connection for feasible construction**[25].

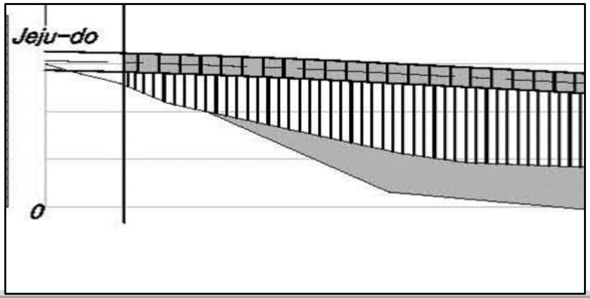
[24] Xiao, J., & Huang, G. (2010). Transverse earthquake response and design analysis of submerged floating tunnels with various shore connections. *Procedia Engineering*, *4*, 233-242.
[25] Mazzolani, F. M., Faggiano, B., & Martire, G. (2010). Design aspects of the AB prototype in the Qiandao Lake. *Procedia Engineering*, *4*, 21-33.

Consideration on boundary connecting module

Numerical study using FLAC2D

- Numerical study on the boundary using FLAC2D
  - ✓ Ground stability analysis on target area (boundary between two different tunnel type)
  - ✓ **Construction environment and geological impact** on tunnel analyzed
  - ✓ Effect of **earthquake** (Ofunato, Hachinohe) on the target area analyzed
  - ✓ **Design for reinforcement will be determined according to the stress concentration on target area.**





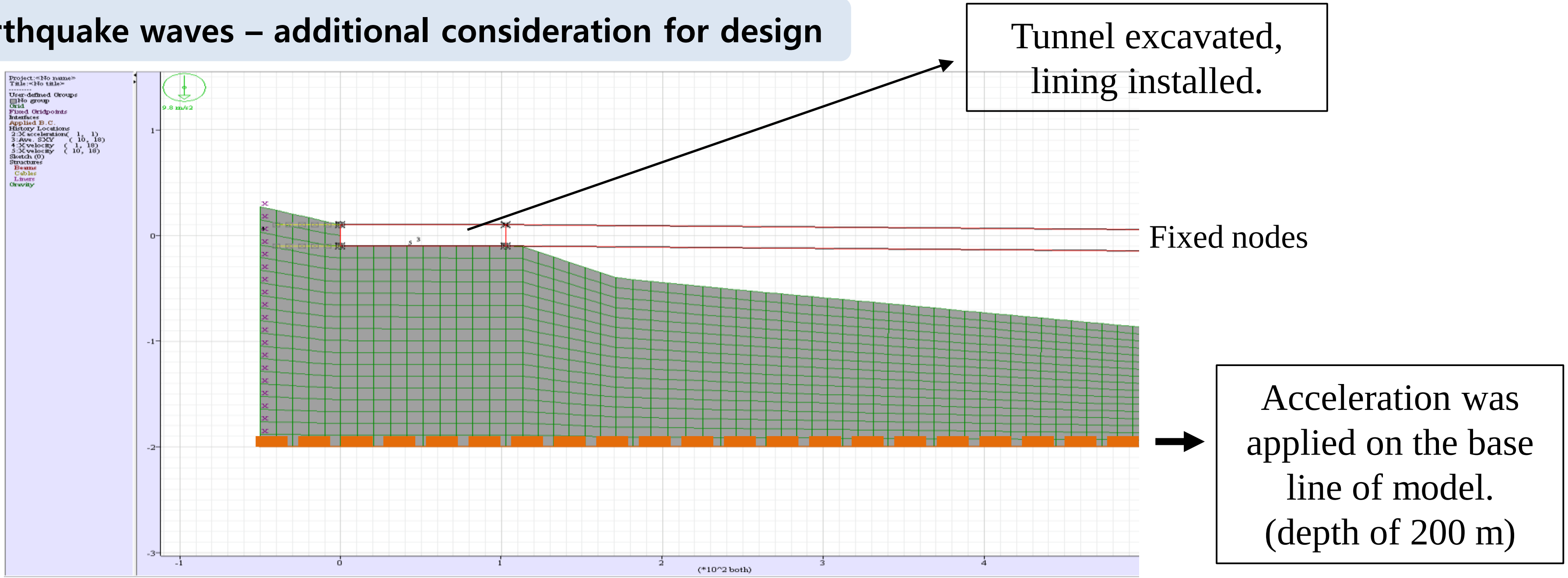
✓ Analysis conditions:

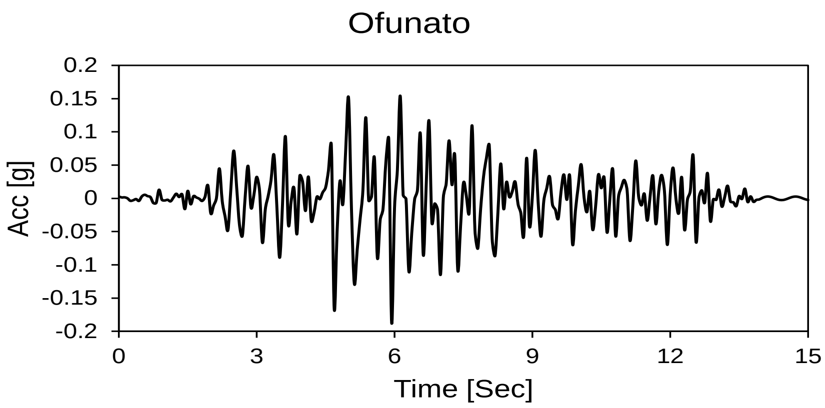
- Target area: Jeju island offshore
- Tunnel diameter 20 m.
- At the boundary, input simplified connecting module as cubic.
- All region is fully saturated.
- BWR (Buoyancy-Weight ratio) is fixed at 1.3.
- No supporting system for floating tunnel was considered

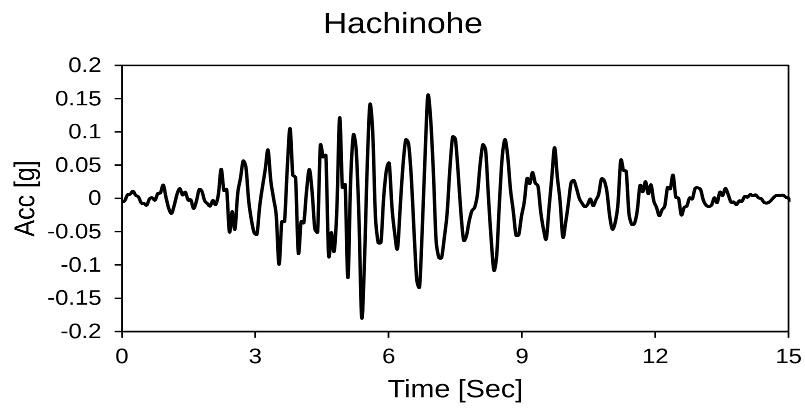
Consideration on boundary connecting module

Numerical study using FLAC2D

Earthquake waves – additional consideration for design



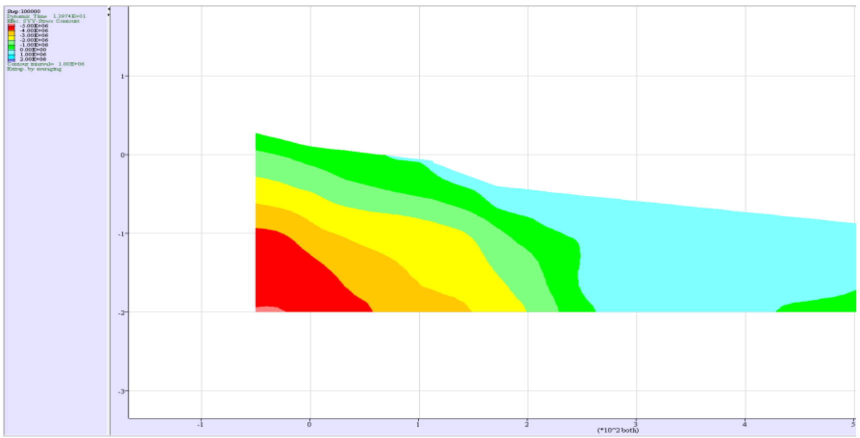




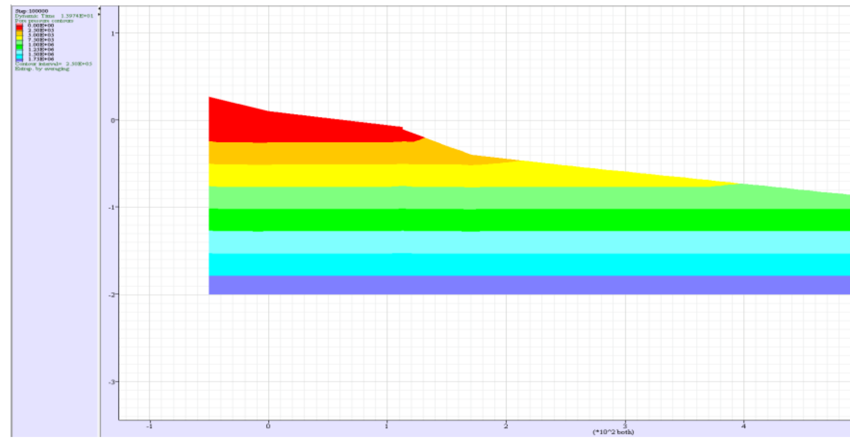
Consideration on boundary connecting module

Numerical study using FLAC2D

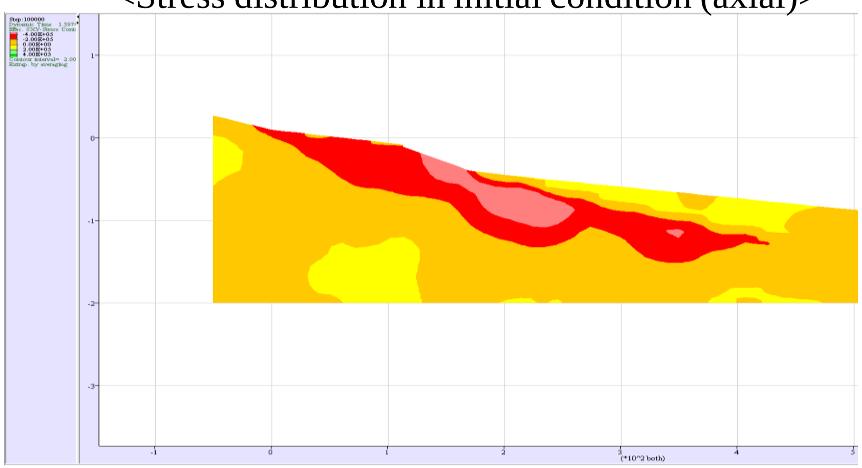
Initial condition (pore pressure & initial stress composed)



<Stress distribution in initial condition (axial)>



<pore pressure distribution in initial condition>



<Stress distribution in initial condition (shear)>

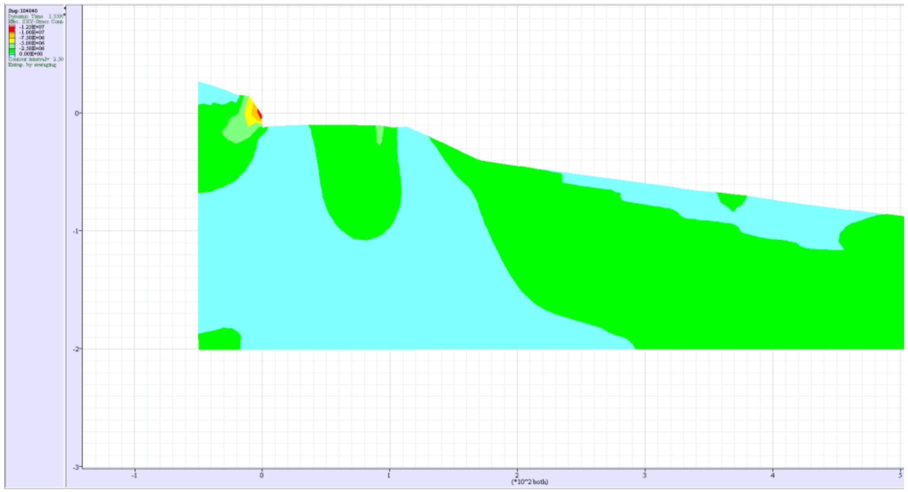
- Two types of ground composition (rock & sand)
- Shear stress concentrated along to the slope
- **Initial stress condition** with **saturated ground** was composed.

Consideration on boundary connecting module

Numerical study using FLAC2D

Earthquake example (Ofunato, short period wave)

<Contour of maximum shear strain increment>



<Contour of shear stress>

- **Maximum shear strain** of 0.6 caused at the **node adjacent to tunnel**.
- Strain have to be controlled with proper reinforcement.

- **Maximum shear stress of 12.5MPa** caused at **the node adjacent to tunnel**.
- Tunnel supporting system has not been considered yet.

Consideration on boundary connecting module

Concluding remarks

- Result of numerical study with FLAC 2D
  - ✓ Jeju island offshore was simulated in numerical software.
  - ✓ Ground behavior adjacent to the tunnel was analyzed when earthquake occurs.
  - ✓ Short period wave (Ofunato) caused stress concentration at the ground near the tunnel with the maximum shear stress of 12.5MPa.
  - ✓ Long period wave (Hachinohe) caused failure at soil-rock interface.
  - ✓ Short period wave has more effect on the target area with rock.

- Forthcoming works
  - ✓ Numerical analysis for calculating stress induced by wave loadings on the boundary
  - ✓ Estimating the maximum allowable stress that can occur on the structure sitting at the boundary
  - ✓ More accurate numerical study is needed using load/moment applied on the floating tunnel.
  - ✓ Utilizing three-dimensional numerical software to consider horizontal stress.
  - ✓ These results will be compiled to conceptualize the connecting module.

Research overview of Group III

Research Center for Smart Submerged Floating Tunnel Systems

KAIST, POSTECH, TEXAS A&M UNIVERSITY, KIOST, DAEWOO E&C, KICT (KOREA INSTITUTE of CIVIL ENGINEERING and BUILDING TECHNOLOGY)

Group I: Design•Analysis

- Analyzing global and local dynamic behavior under extreme and ocean environment loadings
- Design of anchorage-foundation system

KAIST, TEXAS A&M UNIVERSITY, KIOST 한국해양과학기술원

Group II: Materials•Construction

- Chloride-resistant material
- Self-healing concrete technology
- Integrated construction system
- Seabed-ground boundary construction

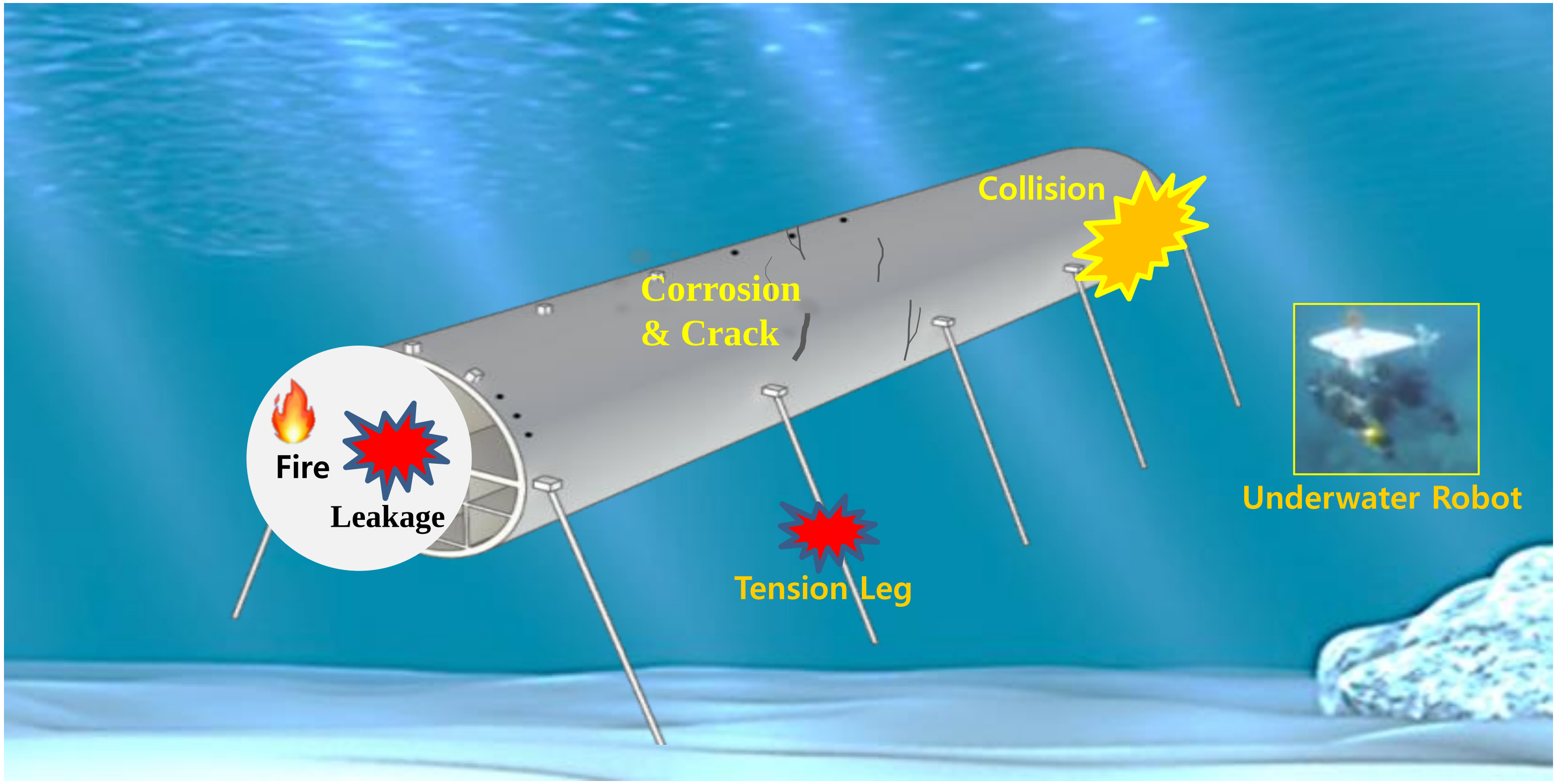
KAIST, DAEWOO E&C

Group III: Monitoring•Maintenance

- Crack/ leakage detection
- Collision detection
- Robot system for maintenance
- Emergency evacuation technology

KAIST, POSTECH, KICT

Research overview of Group III



① Safety response & evacuation for fire and water leakage
② Online monitoring of tension leg force, corrosion, and crack
③ External collision monitoring
④ Robot based underwater topology exploration & sensing

Research overview of Group III

Group Member

[III-1 Sub-group]

SOHN,
Hoon

KAIST

Structural Health Monitoring

[III-2 Sub-group]

JUNG,
Hyungjo

KAIST

Collision and Corrosion Monitoring

[III-3 Sub-group]

YU,
Soncheol

POSTECH

Underwater Robots based Monitoring

[III-4 Sub-group]

LEE,
Seongwon

KICT

Safety Response and Evacuation

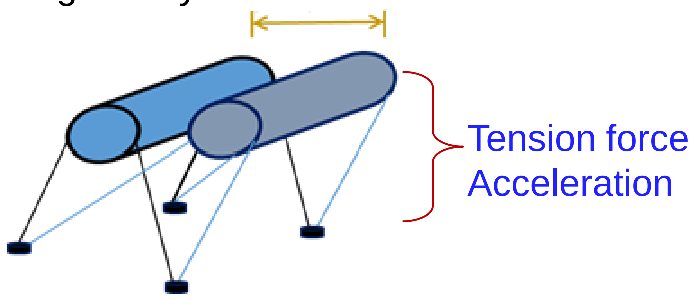
Displacement measurements

Objective

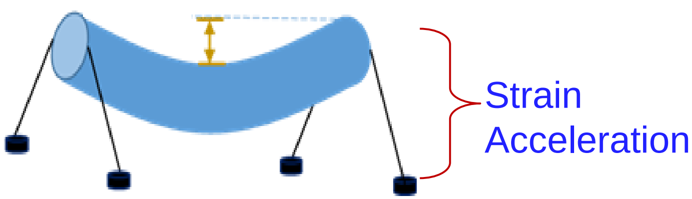
Monitoring of SFT health by estimating displacement via physical quantities, i.e., ① tension force, ② strain, ③ acceleration

Physical Quantities of Displacement

- Rigid body translation



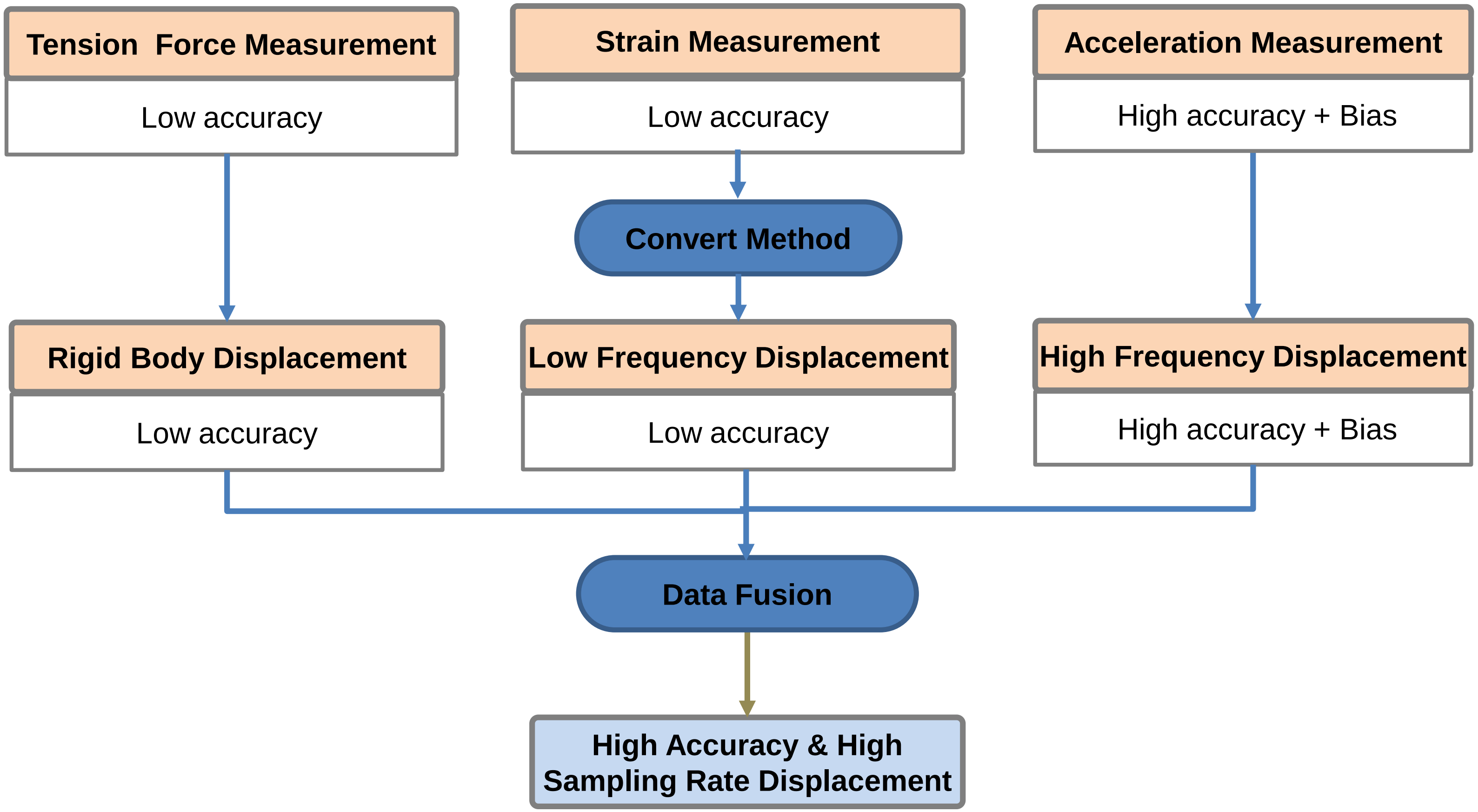
- Deformation



➢ Displacement plays a vital role in structure health monitoring, since it can provide crucial information regarding structural integrity and current conditions.

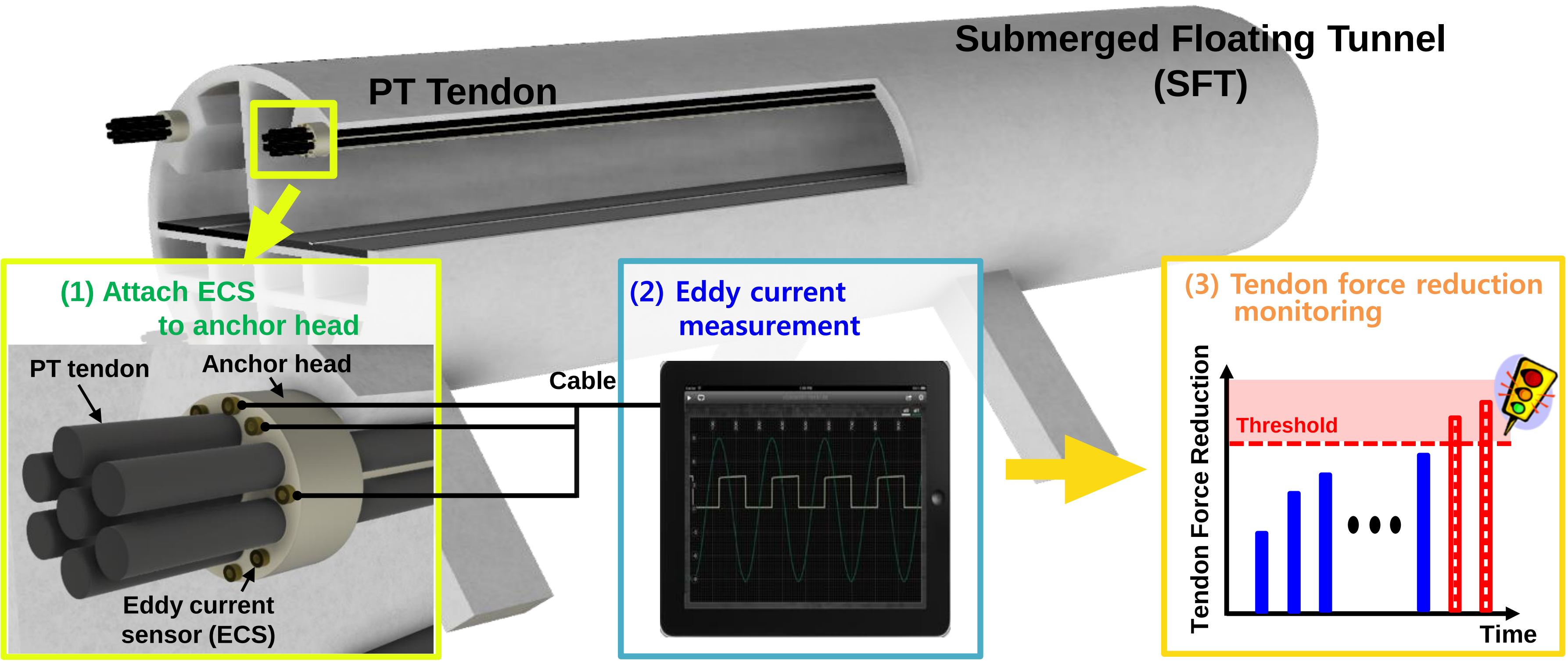
➢ We estimate high-accuracy, high sampling rate displacement by fusing acceleration, strain, and tension force measurements.

Displacement estimation scheme



PT tendon monitoring: Eddy current technique[26]

Objective Monitoring of PT tendon force using eddy current measurement

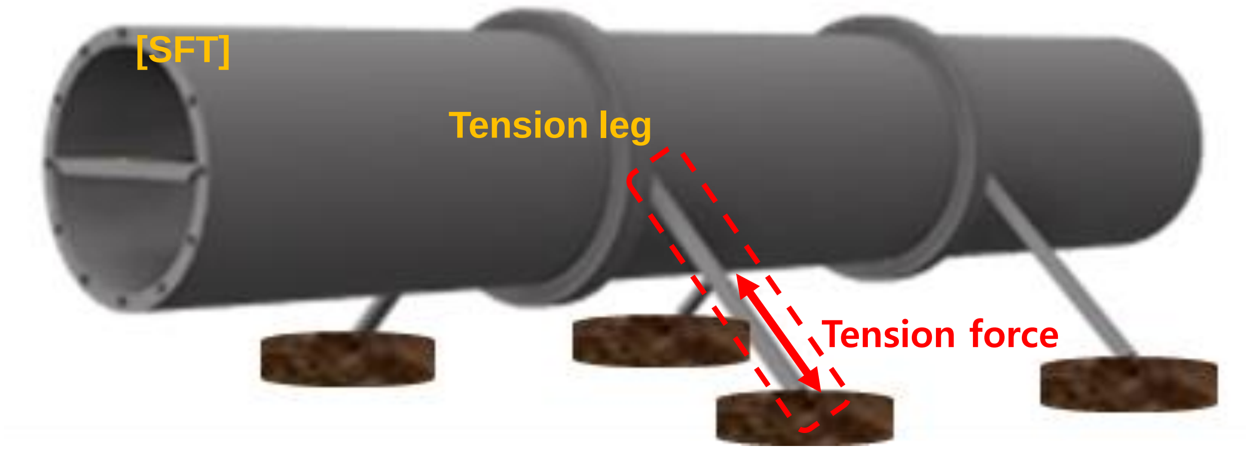


- PT tendon can be a critical load carrying member to maintain desirable performance of SFT.
- If PT tendon force is lost due to "concrete creep", "steel relaxation", or "corrosion", it can cause a catastrophic collapse of the whole SFT system.
- Eddy current technique is developed for monitoring tension force reduction.

[26] Ji-Min Kim, Jun Lee, Hoon Sohn, "Detection of tension force reduction in a post-tensioning tendon using pulsed-eddy-current measurement," Structural Engineering and Mechanics, 65(2), 129-139, 2018.

Tension leg monitoring

Objective Monitoring of tension leg force by developing a low-cost, robust measurement sensor



- Existing technologies for monitoring tension leg forces
  - Load cells & FBG sensors are commonly used
  - Mainly developed for offshore platforms like TLP
  - Very expensive

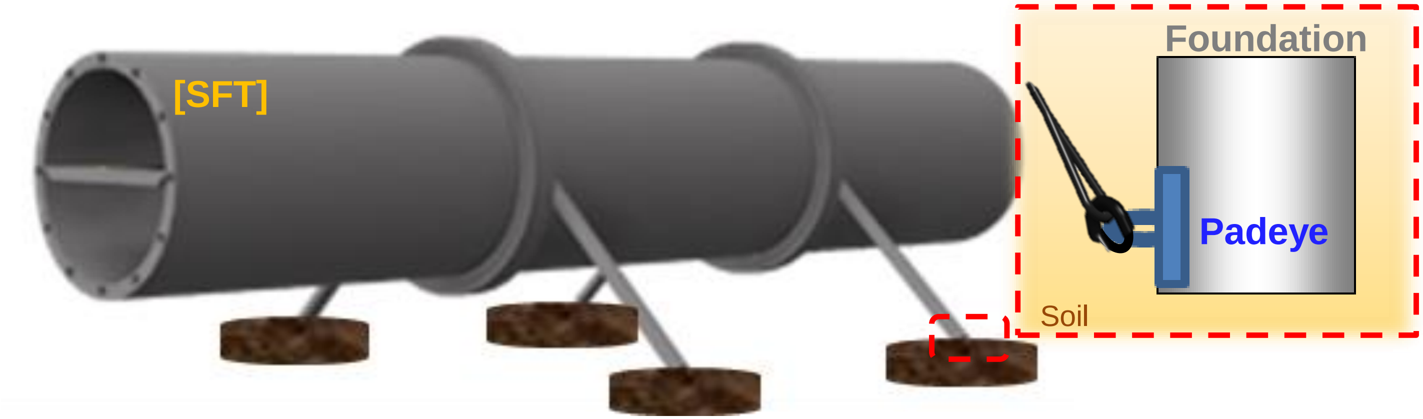
Deploying in underwater environments

➔ Need a development of inexpensive sensor

Anchor monitoring

Objective

- Detect cracks formed at the padeye
- Estimate the remaining life based on nonlinear ultrasonic measurement



Failure Mode of Padeye[29]

- Failure occurs at the ear of the padeye
- The ear of the padeye is the target point of monitoring

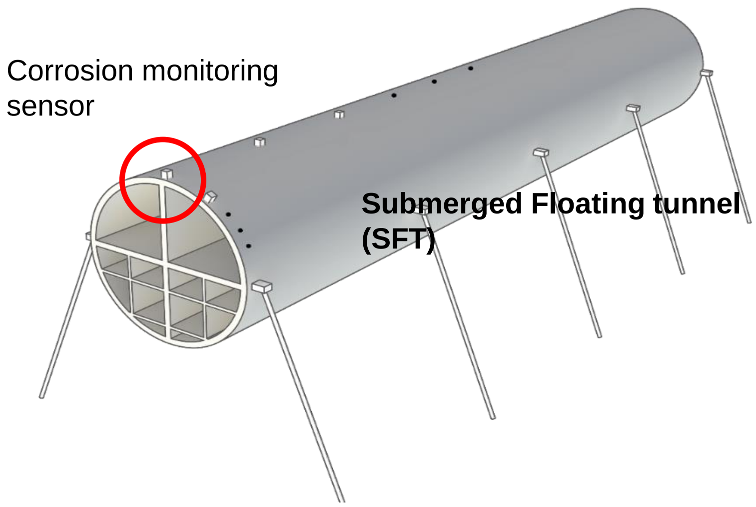
※ We induce failure to be occurred in the padeye at the design stage, even if failure can occur in the shackle.

[29] Philipp, R, Lars, J, Tessa, G, and Andrew, V., "Physical component testing to simulate dynamic marine load conditions", Proceedings of ASME 32nd international conference on ocean, offshore and arctic, 2013.
[30] P. Liu, H.J. Lim, S. Yang, H. Sohn, C.H. Lee, Y. Yi, D. Kim, J. Jung, and I.H. Bae, "Development of a "stick-and-detect" wireless sensor node for fatigue crack detection", Structural Health Monitoring, vol. 16(2), 2017.

Corrosion monitoring

Objective

Develop a corrosion monitoring system so that one can investigate corrosion tendency and penetration characteristics of corrosion factors (i.e., chloride, oxygen, water, etc).



[Corrosion monitoring of SFT in underwater environments]

[Rebar corrosion of reinforced concrete structures][31][32]

[Corrosion monitoring sensor][33]

- Investigation of reinforced concrete rebar corrosion in underwater environments
  - Conventional studies: Inadequate for underwater environments
- Research on the rebar corrosion of SFTs exposed to underwater environments

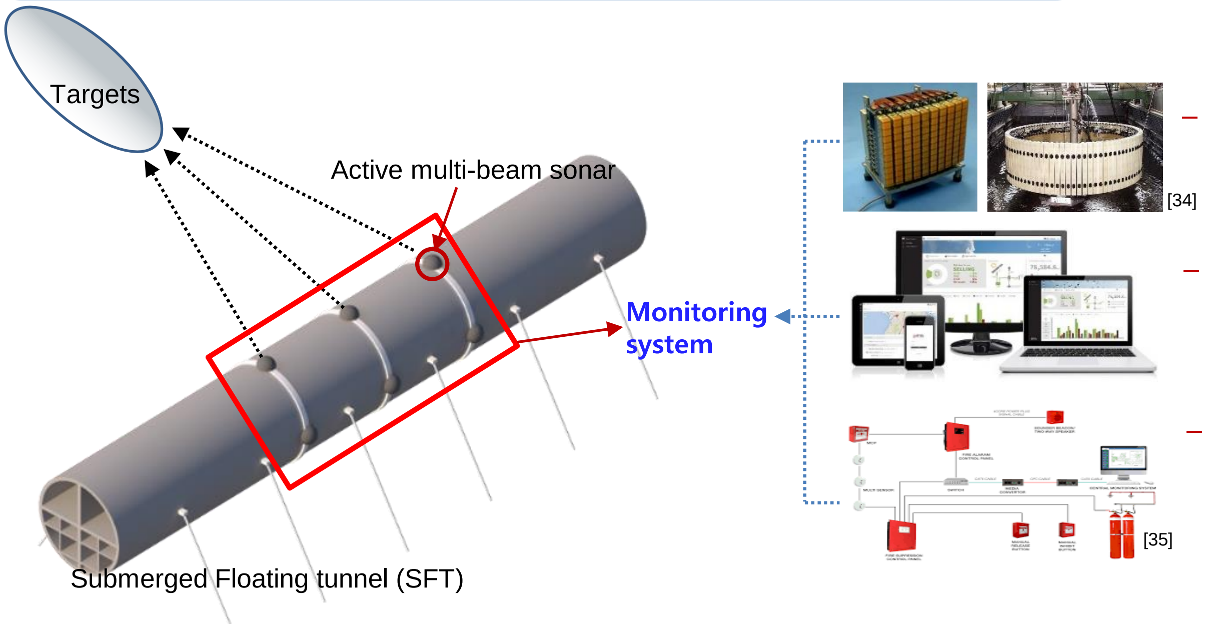
[31] http://hernonkorea.co.kr/index.php?mid=water_crack&document_srl=13000.
[32] http://59.7.251.147/kisTec/amend/amd11002.jsp?defect_cd=AR0412.
[33] https://www.buildingcentre.co.uk/news/circularliving-11.

External collision monitoring

Objective

- Design a collision detection system
- Design a data management module and an alarm system
- Plan the basic design and monitoring scenarios

– **External collision monitoring targets**:
Sinking ship, large anchor, marine structure fragment, drifting object, etc.



– **Collision detection**
Application of collision detection sensors
Performance evaluation of sensors

– **Integrated data management module**
Data processing and management
Connection between sensor and alarm system

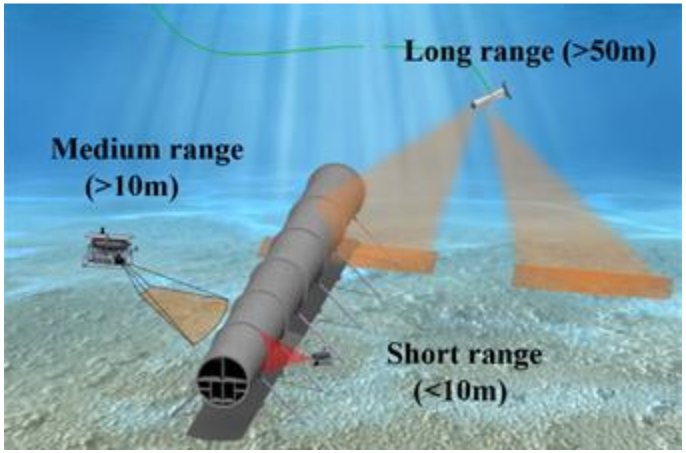
– **Alarm system**
Alarm system configuration
(method, interval etc.)

[Summary of the external collision monitoring system]

[34] https://www.atlas-elektronik.com/who-we-are/competencies.html.
[35] http://airlight.in/ip-based-alarm-system.

Underwater robots based monitoring technology for SFT

Strategy for Underwater Robot Operation



➢ Select the operational strategy according to survey distance

- Long range (side scan sonar) > 50 m
- Medium range (imaging sonar) 10~50 m
- Short range (optical camera) < 10 m

Inspection based on Multi-modal Sensing

➢ Side scan sonar: Scan seabed topography and the entire underwater structure

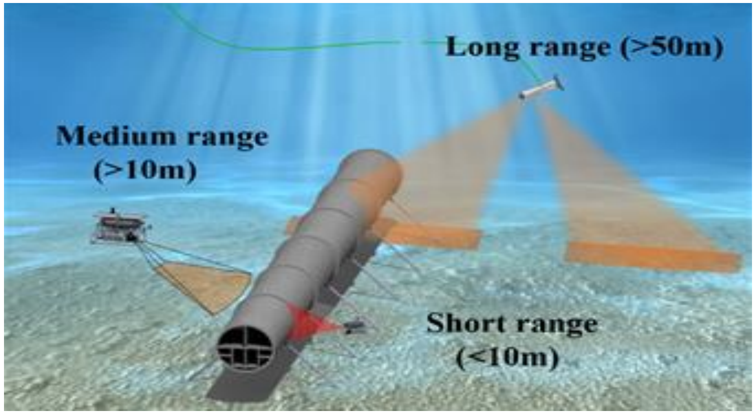
➢ Imaging sonar: Reconstruction of 3D map and recognition of SFT

➢ Optical camera: Precision safety inspection for surface of structure

➢ Research objectives

- Develop strategies to recognize the position of the robot and underwater topology
- Develop an inspection strategy by combining multi-mode sensors such as sonar and camera

Strategy for underwater robot operation



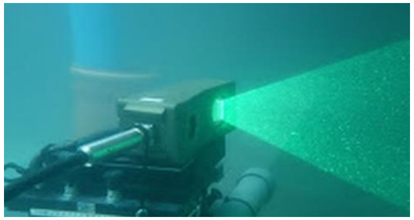
➢ Long range
- Scan wide area including SFT through side scan sonars
- Provide underwater geographic information for studying medium and short ranges based on underwater robots

[36]

➢ Medium range
- Underwater robots with imaging sonars approach to SFTs
- Perform 3D reconstruction of SFTs through the acquired data

[37]

➢ Short range
- Use optical sensors, such as, cameras and lasers
- Perform precise inspection of SFTs' surface



[36] https://www.atlas-elektronik.com/who-we-are/competencies.html.
[37] http://airlight.in/ip-based-alarm-system.

Safety response and evacuation technology for disaster prevention

Emergency Response and Evacuation Technology for Fire

[Smoke propagation distance with ventilation system][38]

- ➢ Early suppression and emergency ventilation
- ➢ Rapid and safe evacuation technology

Emergency Response and Evacuation Technology for Water Leakage

[Example of rock fall and water leakage in tunnel][39]

- ➢ Delay and shutdown for water leakage
- ➢ Rapid and safe evacuation technology

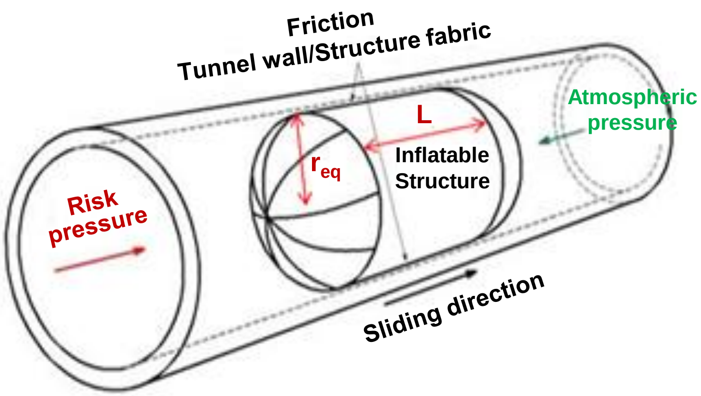
➢ Research objective

- Develop safety response and evacuation technologies for fire & water leakage

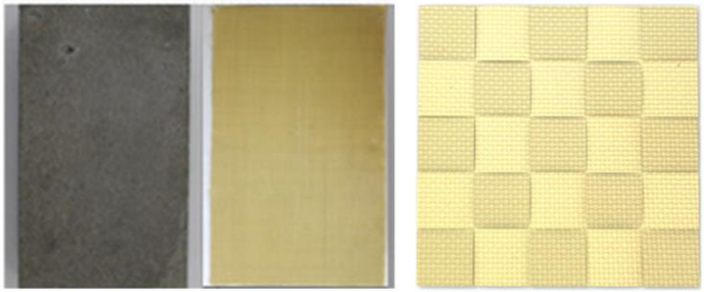
[38] Busan Government Agency, 'Tunnel disaster prevention facility installation and operation plan' 2017
[39] https://rep5355.com/2016/04/06/tunnel-inspection/

Rapid water leak shutdown technology using inflatable system

- **The packed system is inflated by air pressure to block the tunnel**
- **Resist the water pressure by friction resistance between inflator and wall**



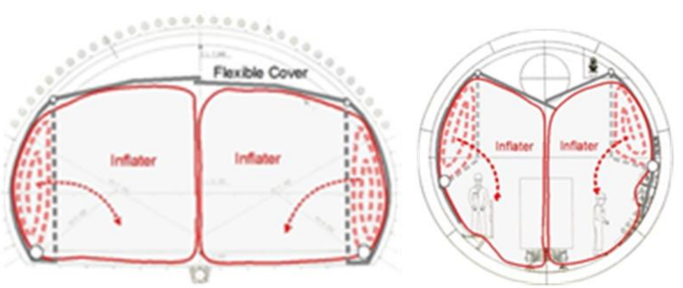
[Design of inflatable structure for rapid shutdown of water leakage][40]



[Materials for inflator][40]

$$L > \frac{r_{eq}}{2\mu},\ \sigma_T^* > \frac{P_{design} r_{eq}}{2}$$

- Water pressure ($P_r = P_w$)
- Equivalent tunnel radius of inflater (r_{eq})
- Design pressure in inflater (P_{design})
- Design friction coefficient (μ)
- Fabric tensile stress (σ_T^*)
- Inflater length (L)



[Split and expansion scenario considering tunnel cross section][40]

[40]Kim H., Kang, S.O., Yoo, K.S., and Kim S.H., "Design considerations and field applications on inflatable structure system to protect rapidly flooding damages in tunnel", J. Korean Tunnelling and Underground Space Association , 2017.

Acknowledgements

This work was supported by the National Research Foundation of Korea Grant funded by the Korea Government (MSIT) (2017R1A5A1014883).


Thank You!