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Scour Stability Evaluation of Bridge Pier Considering Fluid-Solid Interaction

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Outline

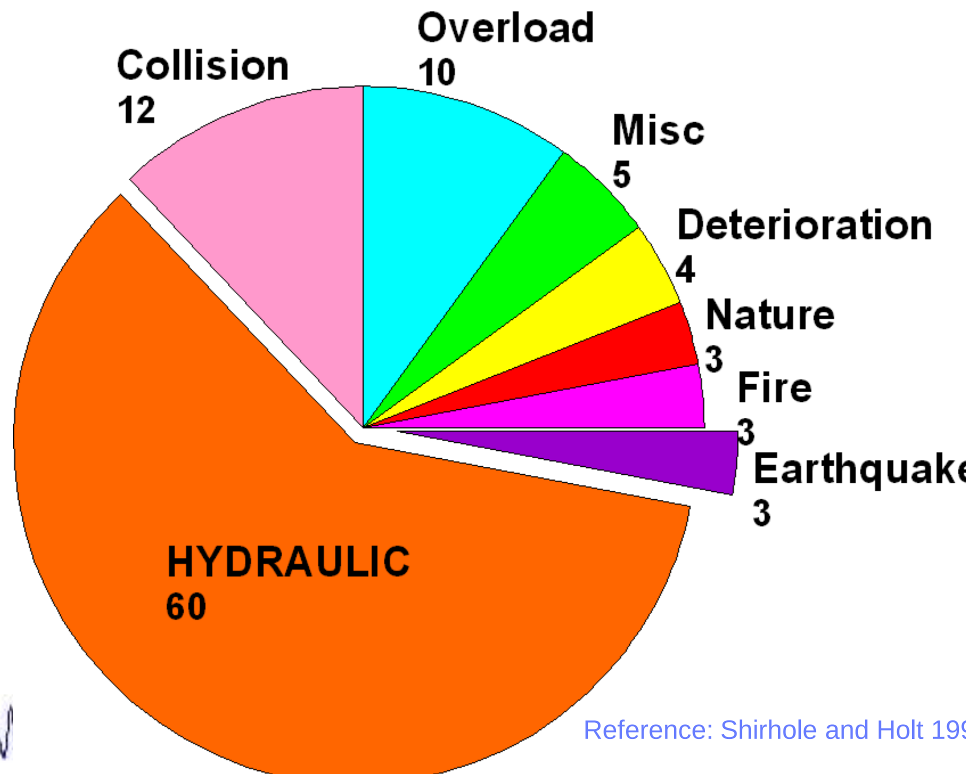
- ***Introduction***
- ***Methodology***
- ***Methodology Verification***
- ***Practical Application***
- ***Summary and Conclusion***

Bridge Failure

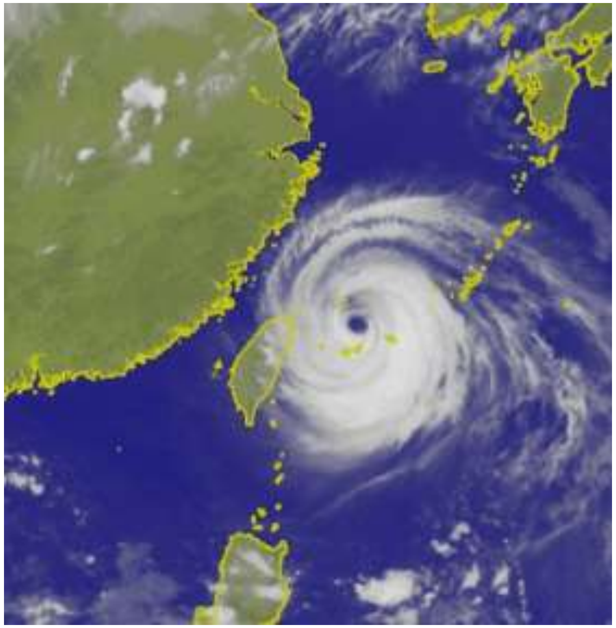
I-5 Skagit River Bridge in the state of Washington (2013)

The Nanfang'ao Bridge collapsed in Taiwan (2019)

- Scour is one of the major causes for bridge failure.
- More than 1000 bridges have collapsed over the past 30 years in the U.S., with 60% of the failures due to scour.

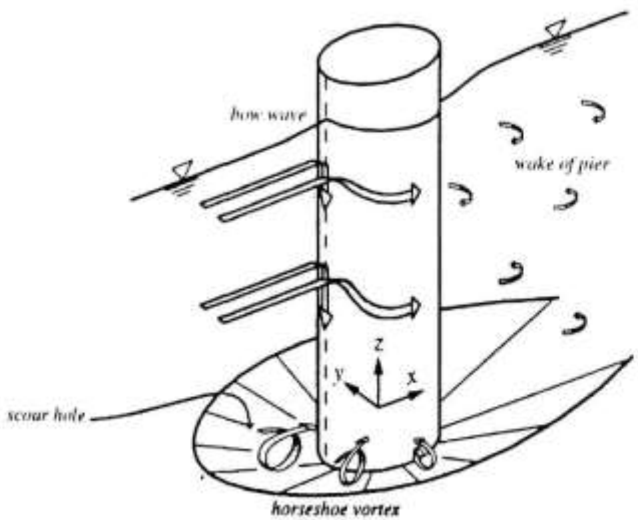


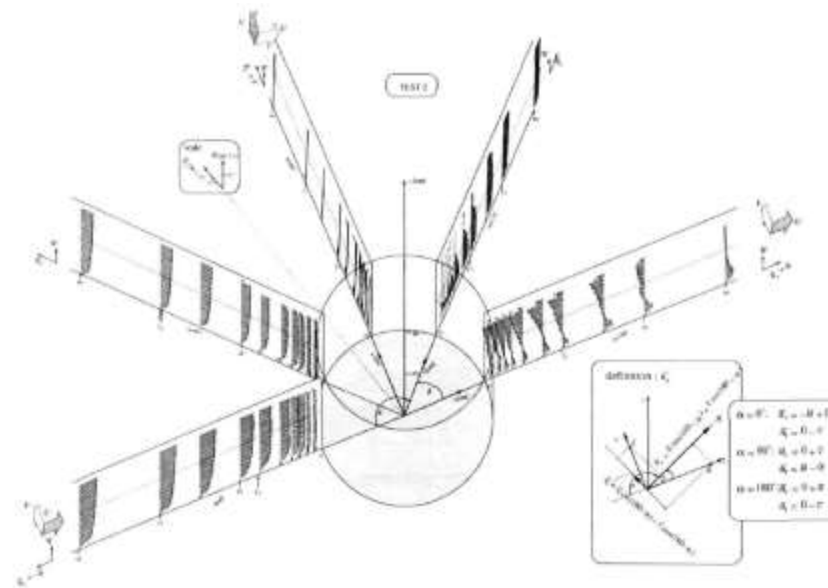
Reference: Shirhole and Holt 1991



- Typhoon and hurricane can bring intensive rainfall in short term of time.
- flash flood or other flood hazard may occur in catchment area with bad soil and water conservation.
- Scouring and sedimentation happen everywhere at riverbed.
- When water flows by obstacle, such as pier and abutment, scouring may have significant impact on bridge stability.

- Flow pattern and vortex around cylinder or scoured pier have been descripted by Graf and Altinakar(1998), Graf W.H. and B. Yulistiyanto(1998) and other researchers.
- Fluid behavior associated to scouring can be concluded into 3 types: downward flow, horseshoe vortex and wake-vortex system



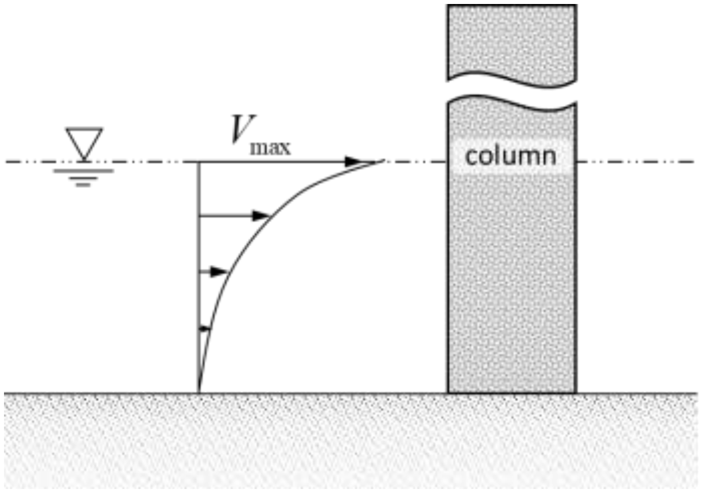


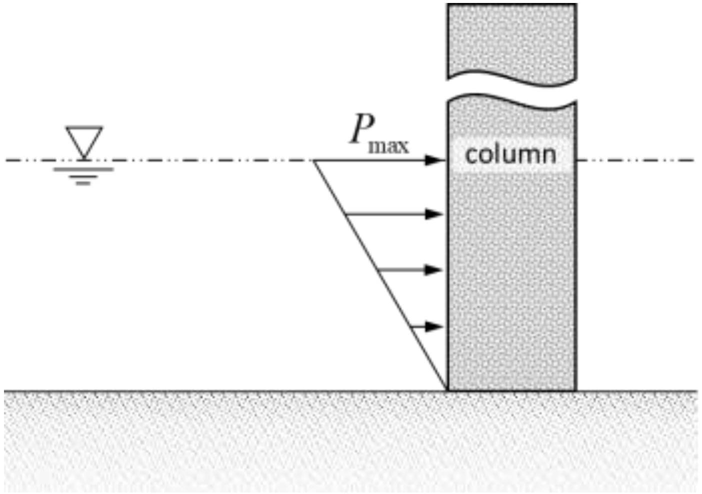
- However, most current regulations simplified the complicated fluid behavior into parabolic current speed and linear current force to conduct static evaluation.

- The negligence of nonlinear force generated by fluid flow might cause overestimation of pier stability.

$$P_{avg} = 52.5K\left(V_{avg}\right)^2$$

$$P_{\max} = 2P_{avg}$$





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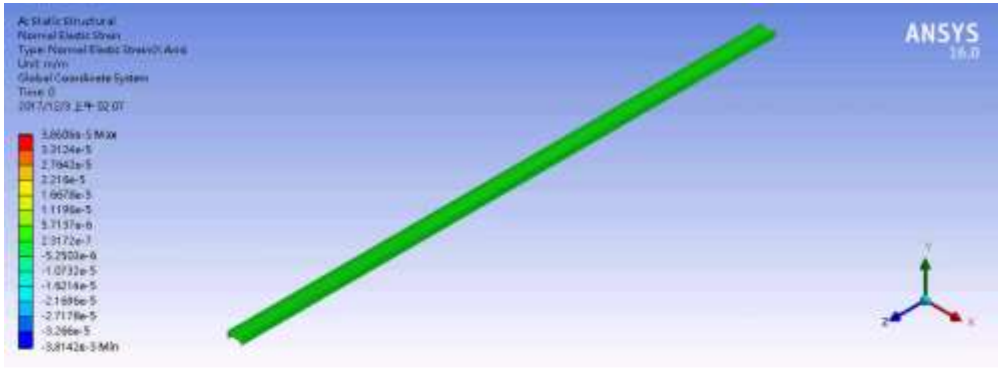
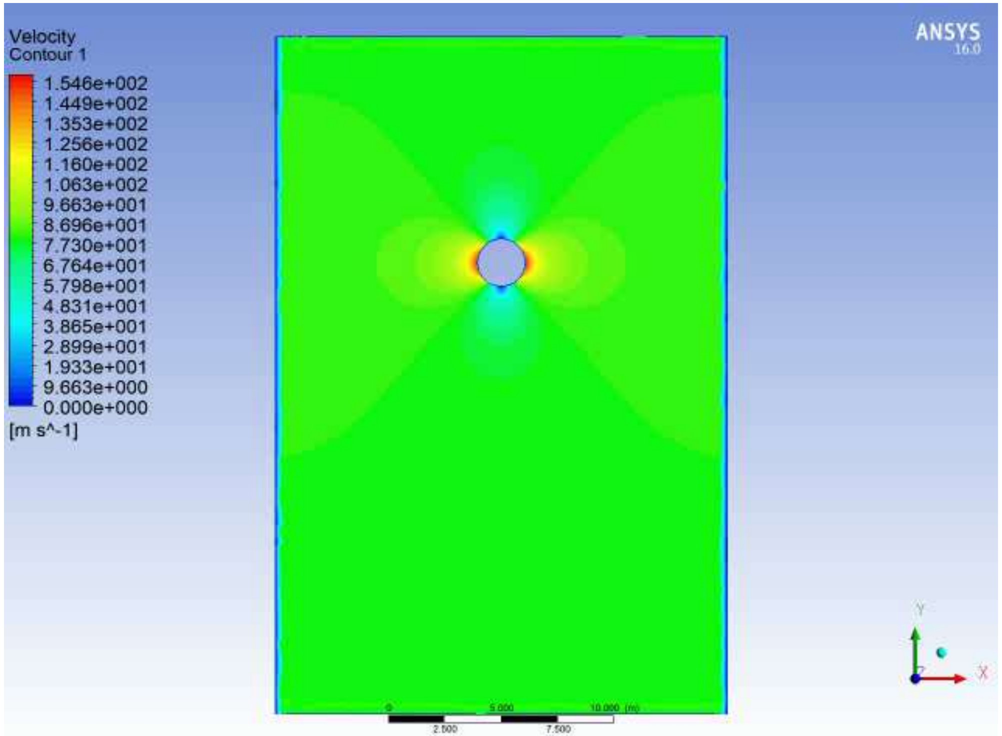
Numerical simulation

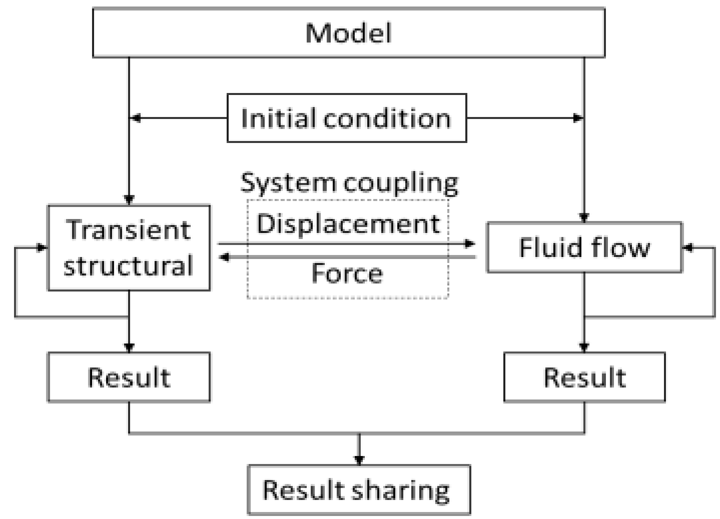
- For most finite element simulation program, solid and fluid simulation work separately, meaning fluid and solid condition can not be considered simultaneously.

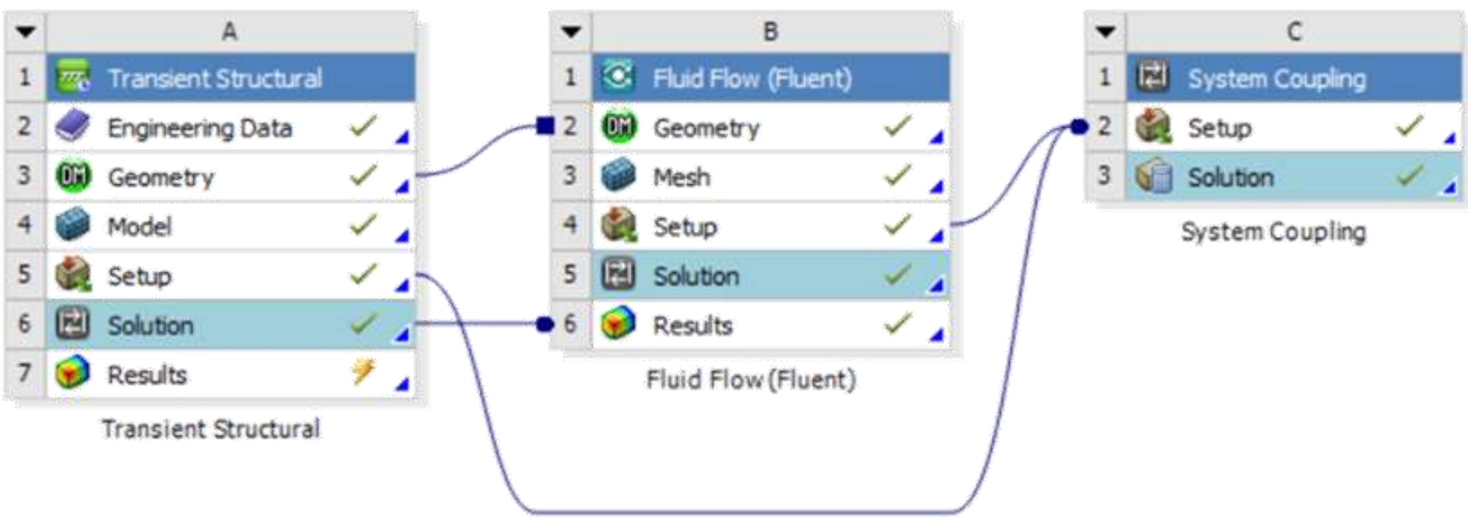
- Finite element simulation program ANSYS is applied to conduct static and dynamic fluid-solid interaction (FSI) simulation.





- By using system coupling, result from both solid and fluid simulation system is transferred to each other as the boundary condition of next time interval.

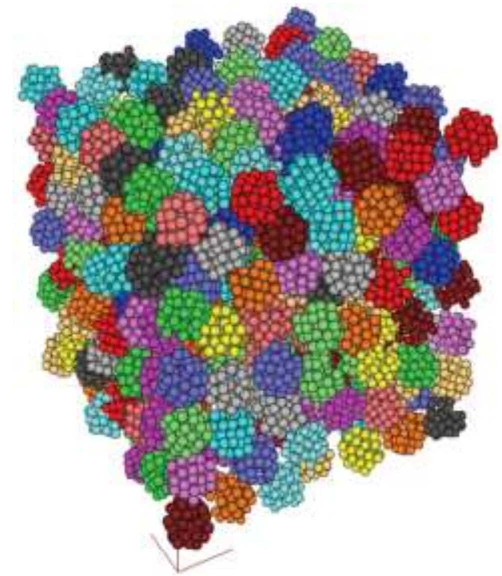


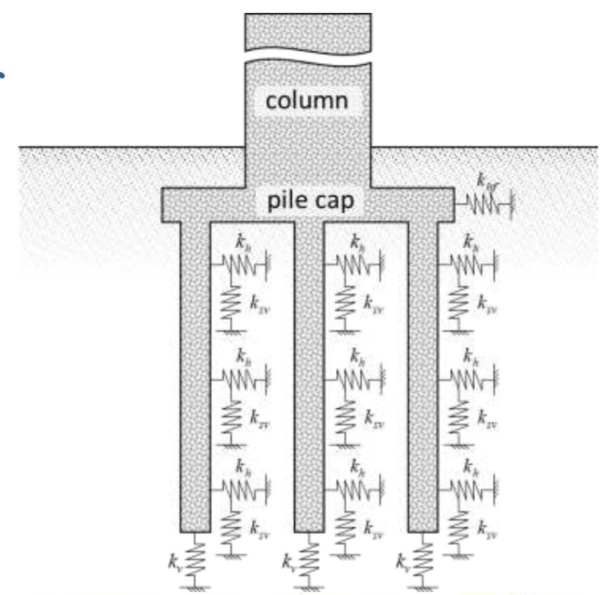


- In order to simulate soil behavior, several methods such as solid elements, discrete element method (DEM) and soil spring are applied.

- Solid elements and DEM required detailed soil parameters and powerful operation ability of hardware.

- Soil spring model is applied and set on the model in three different types.





- Referring to *Seismic Design Specification* of Taiwan, the soil spring model includes four different types of spring:
  - Horizontal pile soil spring

$$k_h = 0.34(\alpha E_0)^{1.10} D^{-0.31} (EI)^{-0.103} \qquad E_0 = 28N$$

  - Horizontal pile cap soil spring

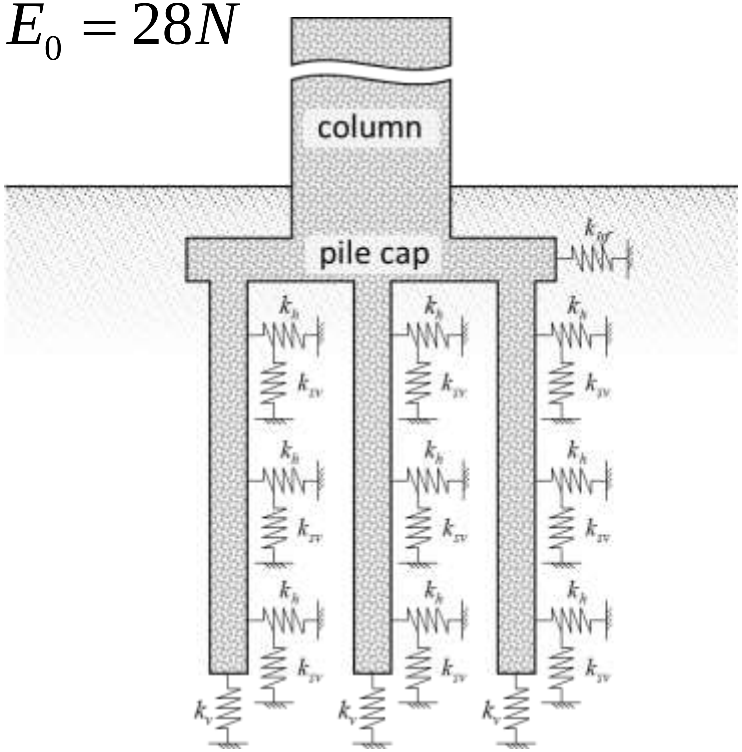
$$k_{hf} = k_{h0}\left(\frac{B_H}{30}\right)^{-3/4} \qquad k_{h0} = \frac{(\alpha E_0)}{30}$$

  - Vertical pile toe soil spring

$$k_v = k_{v0}\left(\frac{B_v}{30}\right)^{-3/4} \qquad k_{v0} = \frac{(\alpha E_0)}{30}$$

  - Vertical pile soil spring

$$k_{sv} = 0.3k_h$$



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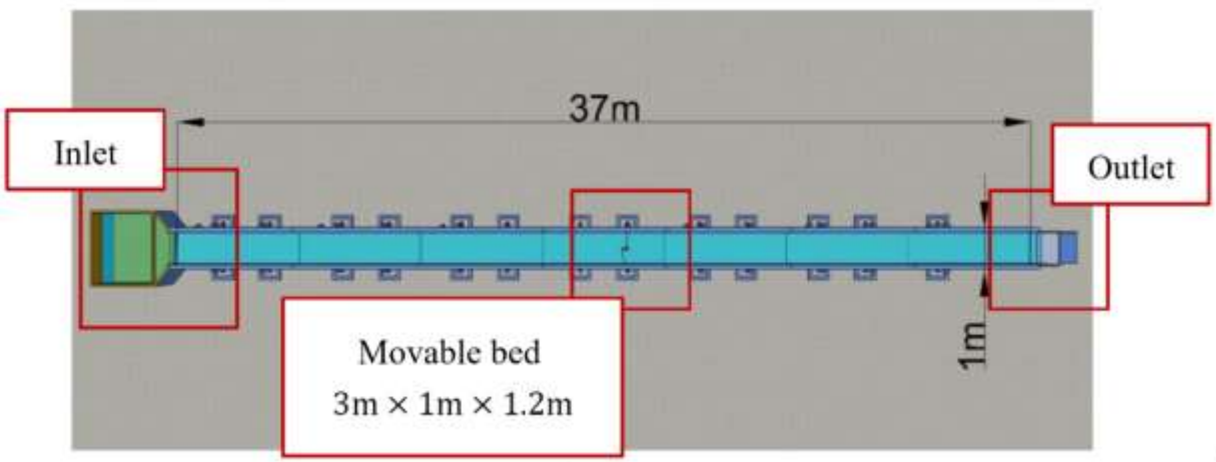
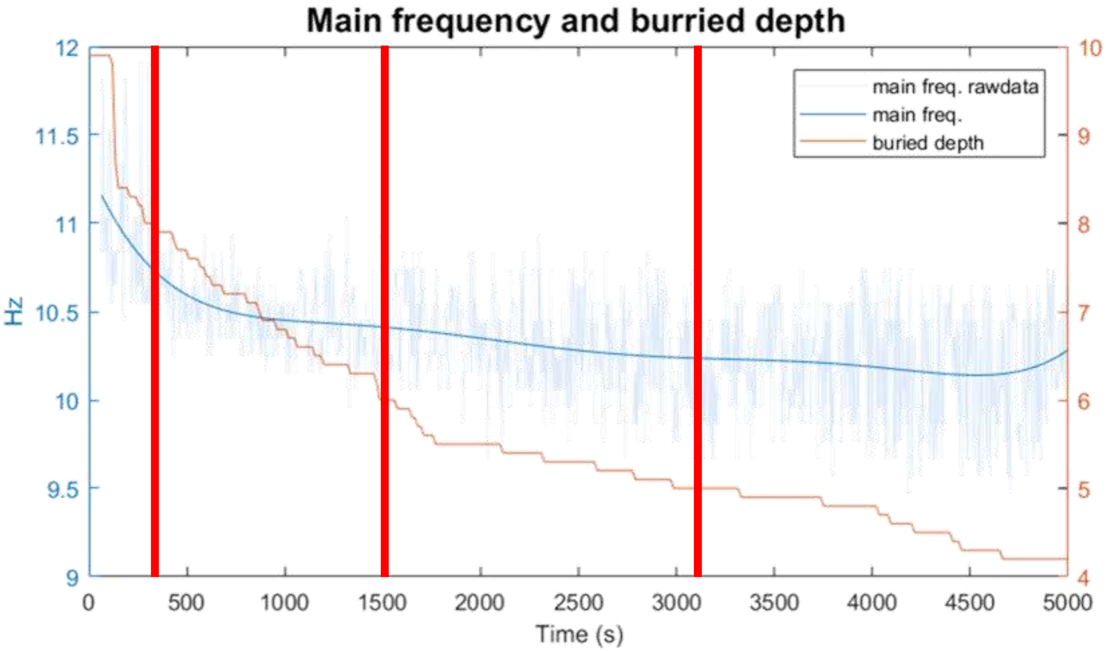
Scaled scour experiment

- As only few studies applying FSI system to scour pier simulation, it is necessary to verify the applicability of FSI system.
- A scaled scour test with 12 cm initial buried depth and 2.5 m/s flow velocity was conducted for verification.
- Velocity meters are set on top of pier model to collect the vibration in 3 directions.



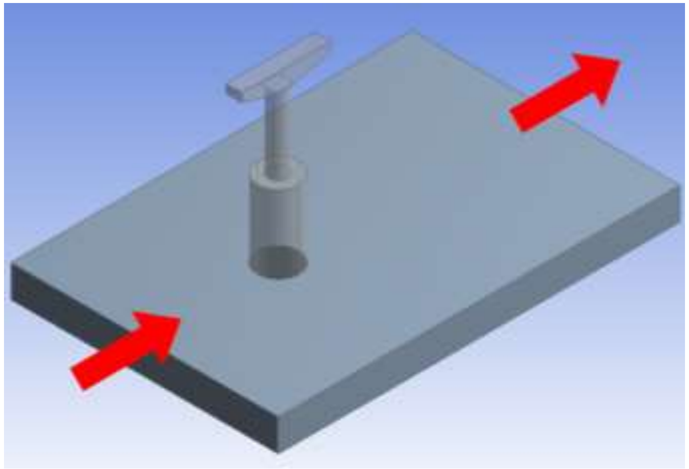
- By using STFT, main frequency of pier model at each time in the current direction is identified.
- 3 boundary conditions (8, 6, 5 cm) are selected for numerical simulation

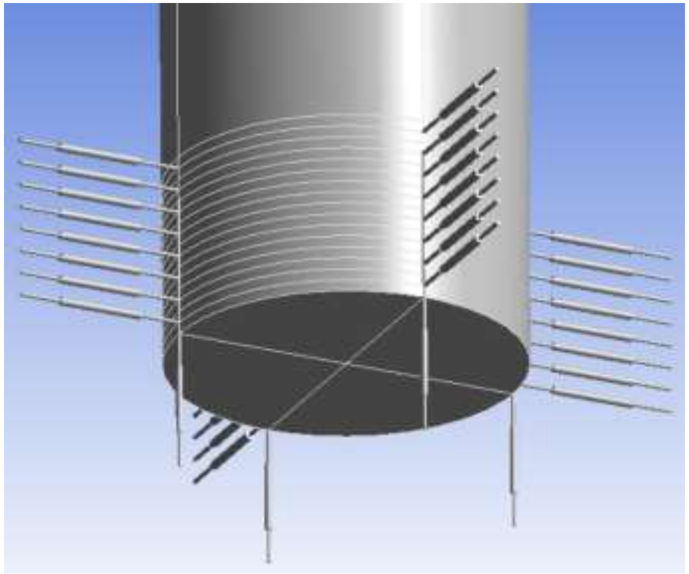


Buried depth (cm)	8	6	5
Freq. (Hz)	10.76	10.41	10.21
Water depth (cm)	10.69	10.44	10.08

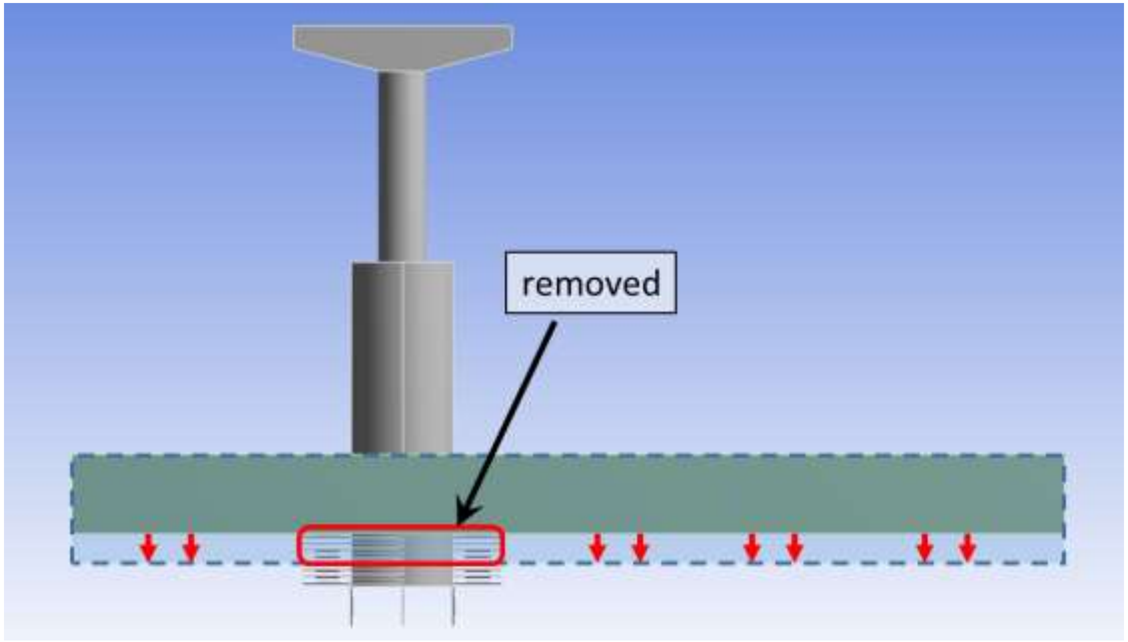
- Pier model is surrounded by a 100 x100 cm fluid block. The current speed is increased gradually to 2.5m/s.

- Springs are set in current, vehicle and vertical direction. To prevent lack of stability, each soil spring is separated to several parts and set evenly on the model.

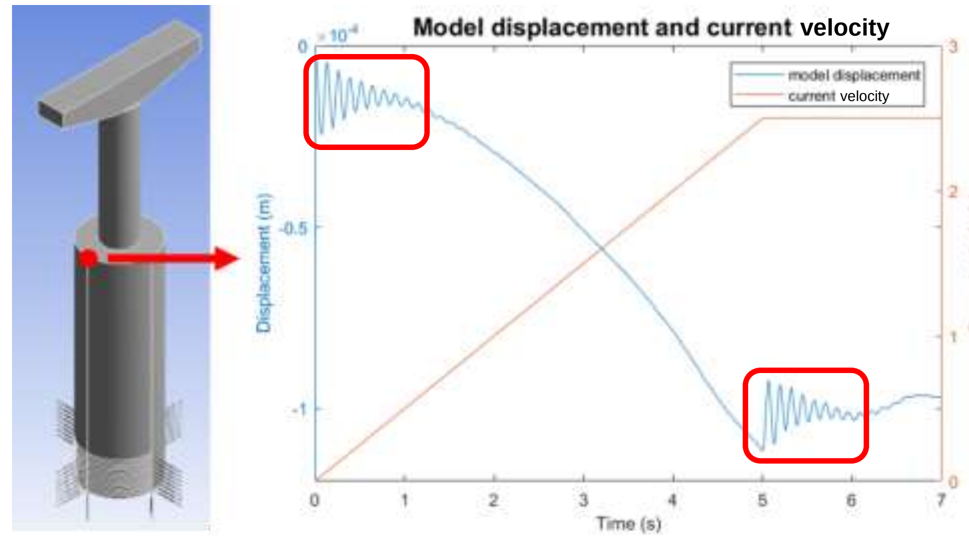




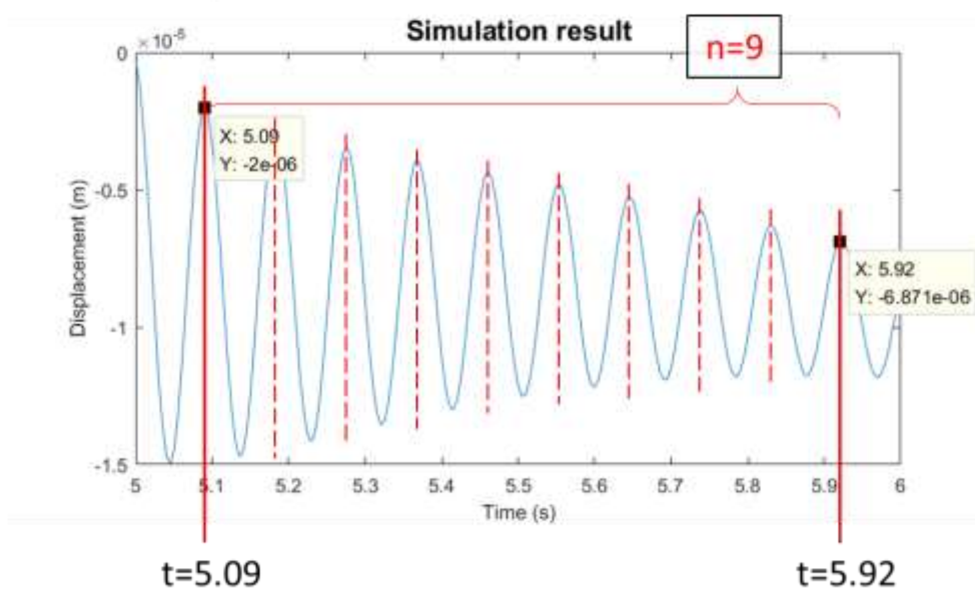
- The boundary condition is unchangeable during FSI simulation.
- Scour simulation is conducted by adjusting the depth of fluid block and setting of soil spring.



- Due to the setting of flow velocity, two free decay signals with same frequency appear at start of simulation and steady flow velocity part.



- Structural response at steady flow velocity is collected to calculate the dominant frequency of the model.



- While having 25% (2 cm scour) and 37.5% (3 cm scour) bed material loss, numerical model has only 3.2% and 5% error on fundamental frequency.
- Numerical model fits the test model well while the boundary condition of embedded depth is changed.

Embedded depth (cm)	**8**	6	5
Freq. (experiment)	**10.76**	10.41	10.21
Freq. (simulation)	**10.77**	10.07	9.70
Error	**0.1%**	3.2%	5.0%

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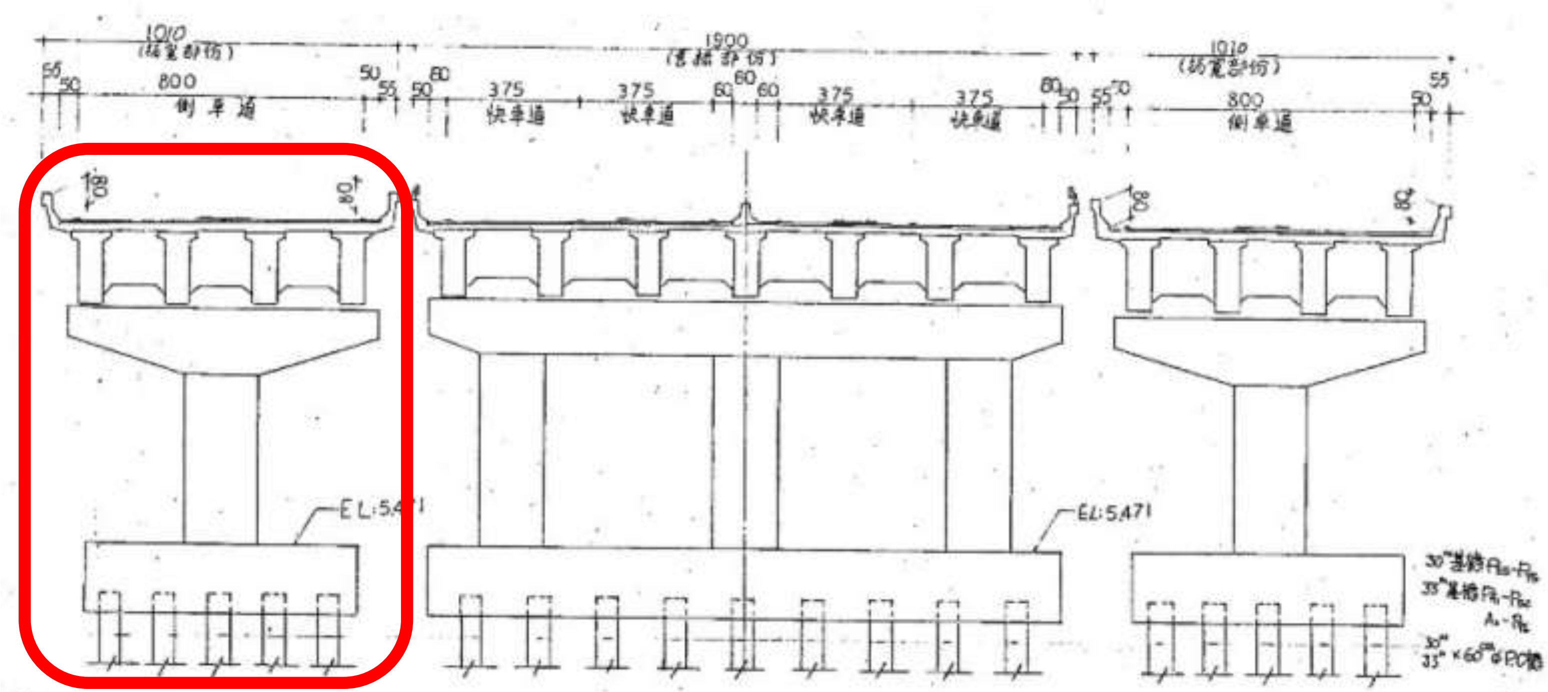
- Located in western Taiwan, Xi-Bin bridge is one of the most important bridges of western traffic line.
- Connecting ChangHua and YunLin county, Xi-Bin bridge crosses the longest river in Taiwan, Chou-shui river.

Xi-Bin Bridge

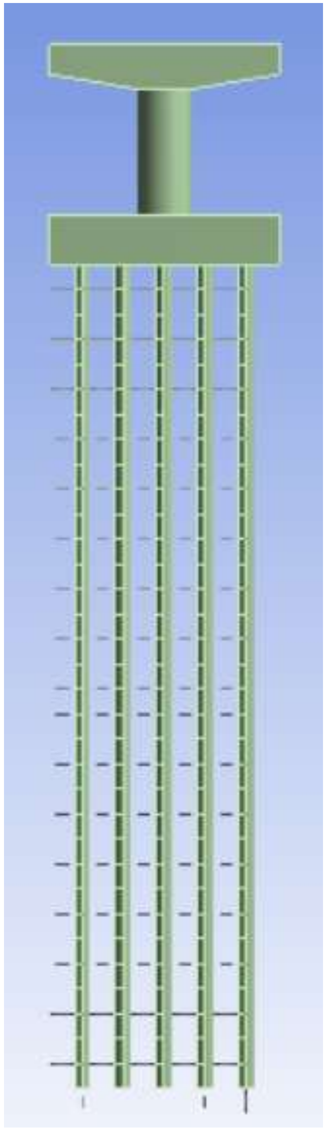
- The bridge includes a 4-lane original bridge and two 2-lane extension bridges.
- The 16th pier at the extension bridge is built in FSI system and conducted with both static and FSI simulations.

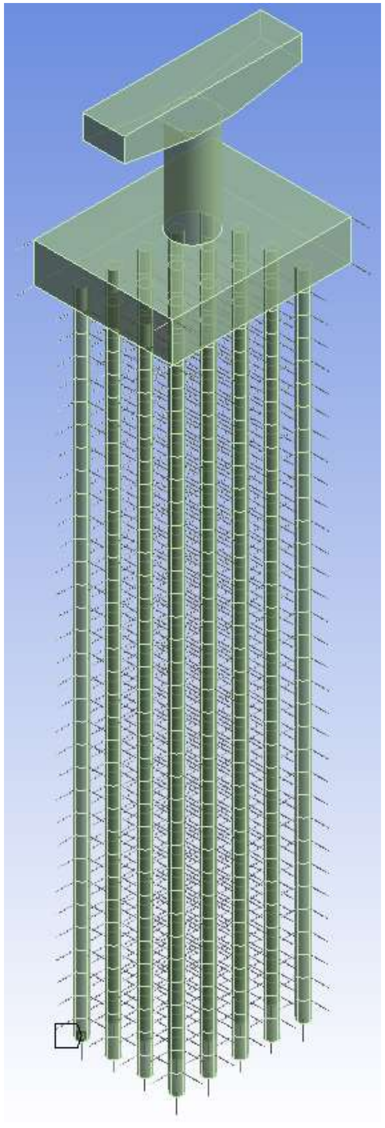


Extension Bridge | Original Bridge | Extension Bridge

Numerical model

- Considering the complexity of the model, the hollow RC pile is simplify to solid concrete pile.
- Soil springs are placed in array, and model will not tip without external force.
- Horizontal and vertical soil spring are set each meter at the up stream and right side of pile.





FSI simulation setting :

- Time interval:
  0.1 s
- Simulation time:
  8-21 s
- Total step:
  80-210
- Max iterations:
  7
- Fluid data output freq.:
  50 steps

Outline of Schematic C1: System Coupling

	A
1	System Coupling
2	Setup
3	Analysis Settings
4	Participants
5	Transient Structural
6	Regions
7	Fluid Solid Interface
8	Fluid Flow (Fluent)
9	Regions
10	fluid_solid_interface
11	wall-solid
12	Data Transfers
13	Data Transfer
14	Data Transfer 2
15	Execution Control
16	Co-Sim. Sequence
17	Debug Output

Properties of Analysis Settings

	A	B
1	Property	Value
2	Analysis Type	Transient
3	Initialization Controls	
4	Coupling Initialization	Program Contr...
5	Duration Controls	
6	Duration Defined By	End Time
7	End Time [s]	8
8	Step Controls	
9	Step Size [s]	0.1
10	Minimum Iterations	1
11	Maximum Iterations	7

- Three boundary conditions including scour depth, flow velocity and water level are considered.

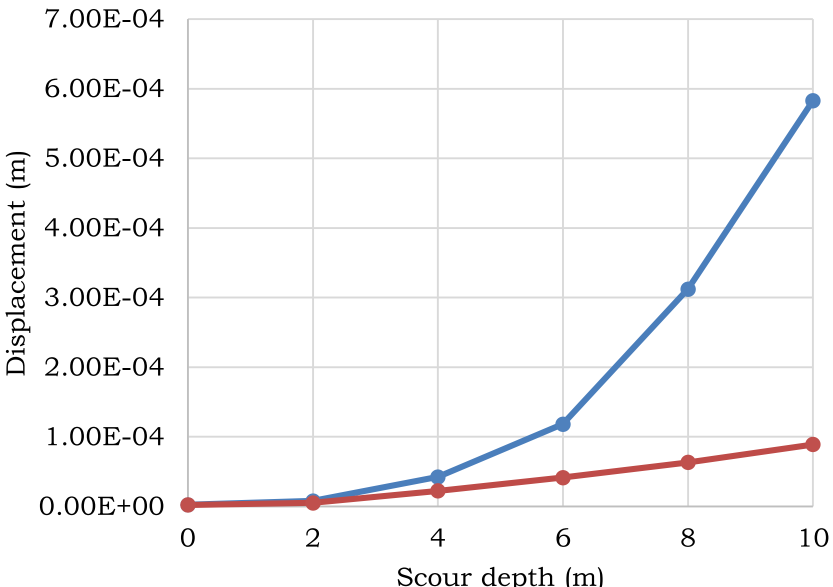
- Sensitivity analysis is conducted by comparing the response under 10m scour, 0.5m/s flow velocity and water level at EL.8.38m (3m above pile cap).
- Scour depth and flow velocity are found out to control response of model.

Scour depth	**10**	8	6	4	2	0
Disp.	**5.83E-04**	3.12E-04	1.18E-04	4.24E-05	7.94E-06	2.30E-06
%	**-**	46.44	79.73	92.73	98.64	99.60
Flow velocity	**0.5**	1	1.5	2		
Disp.	**5.83E-04**	1.26E-03	1.88E-03	2.92E-03		
%	**-**	116.35	222.40	401.72		
Water level	**3**	5	1			
Disp.	**55.83E-04**	5.55E-04	5.28E-04			
%	**-**	4.75	9.47			

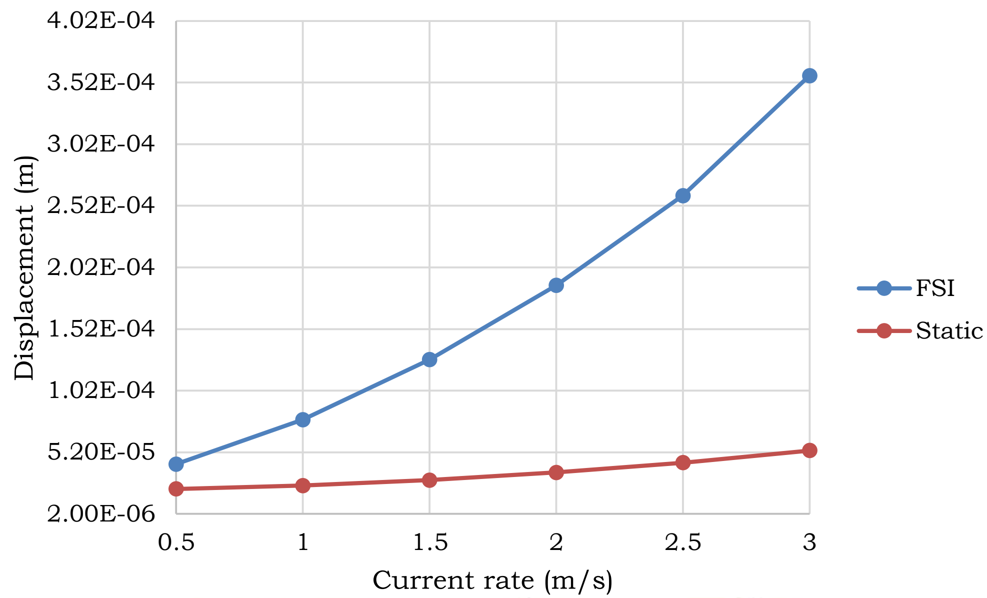
- Simulation result of the case with 4m scour and 0.5m/s flow velocity is selected for comparison

- It shows that the dynamic response is larger while considering fluid behavior, under the same scour depth or current speed.

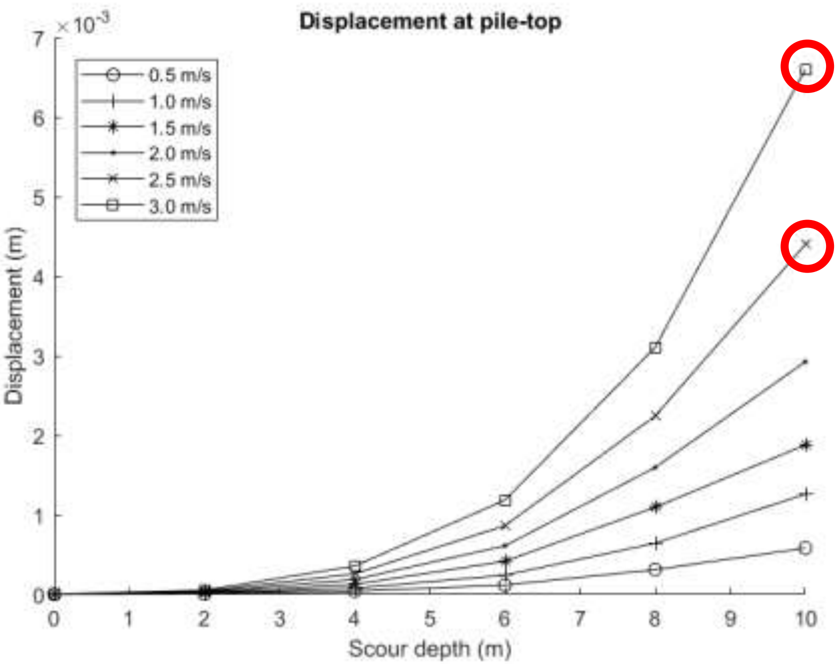
0.5m/s flow velocity

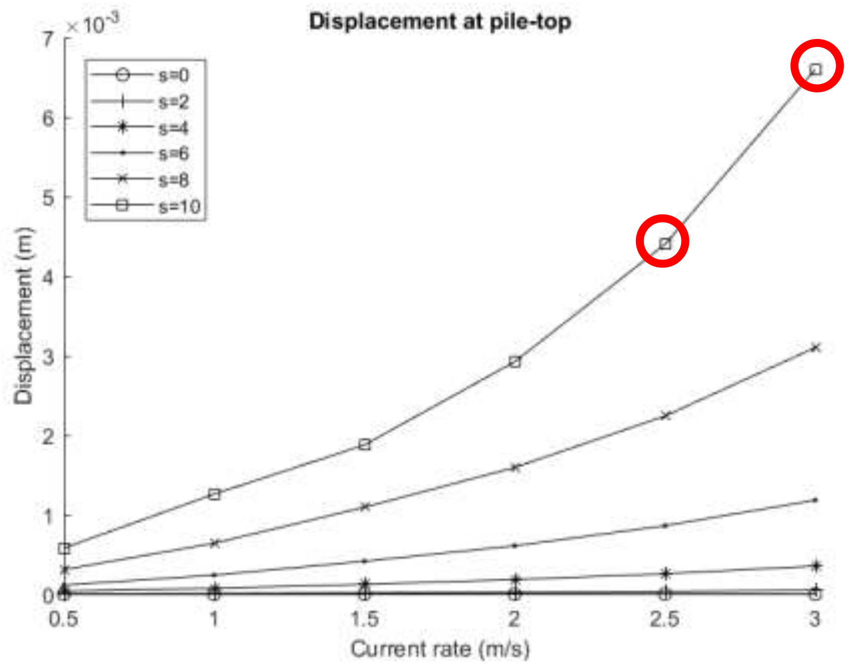


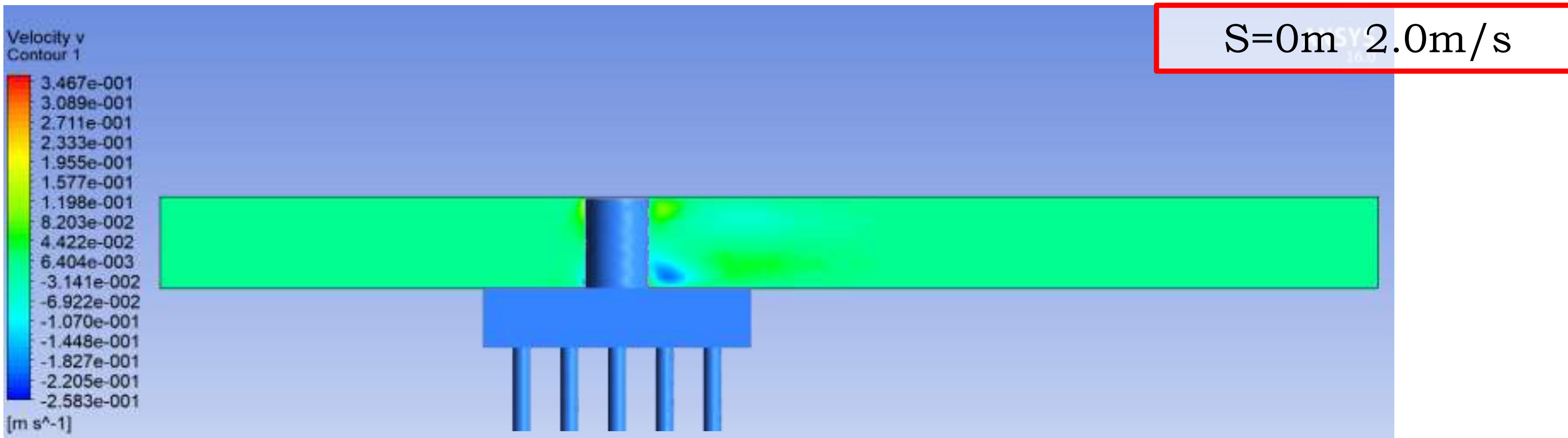
4m scour depth

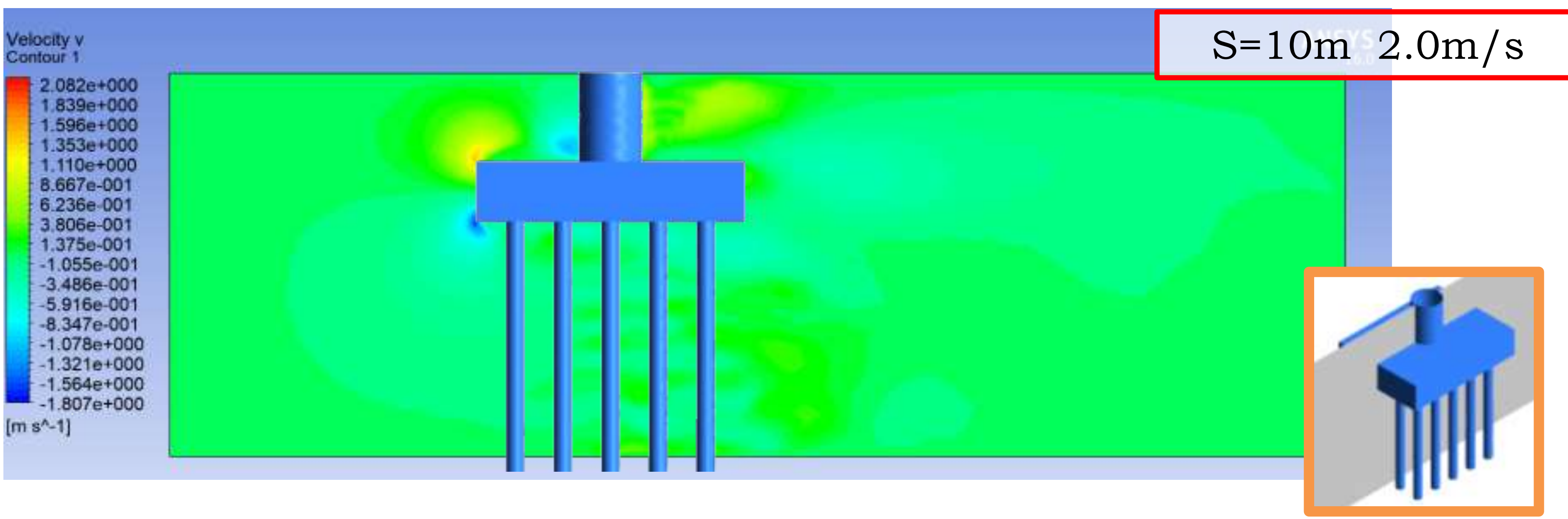


- 70 simulation cases are conducted with static and FSI system with 6 different flow velocity and scour depth condition.
- Structural response at pile top is collected.

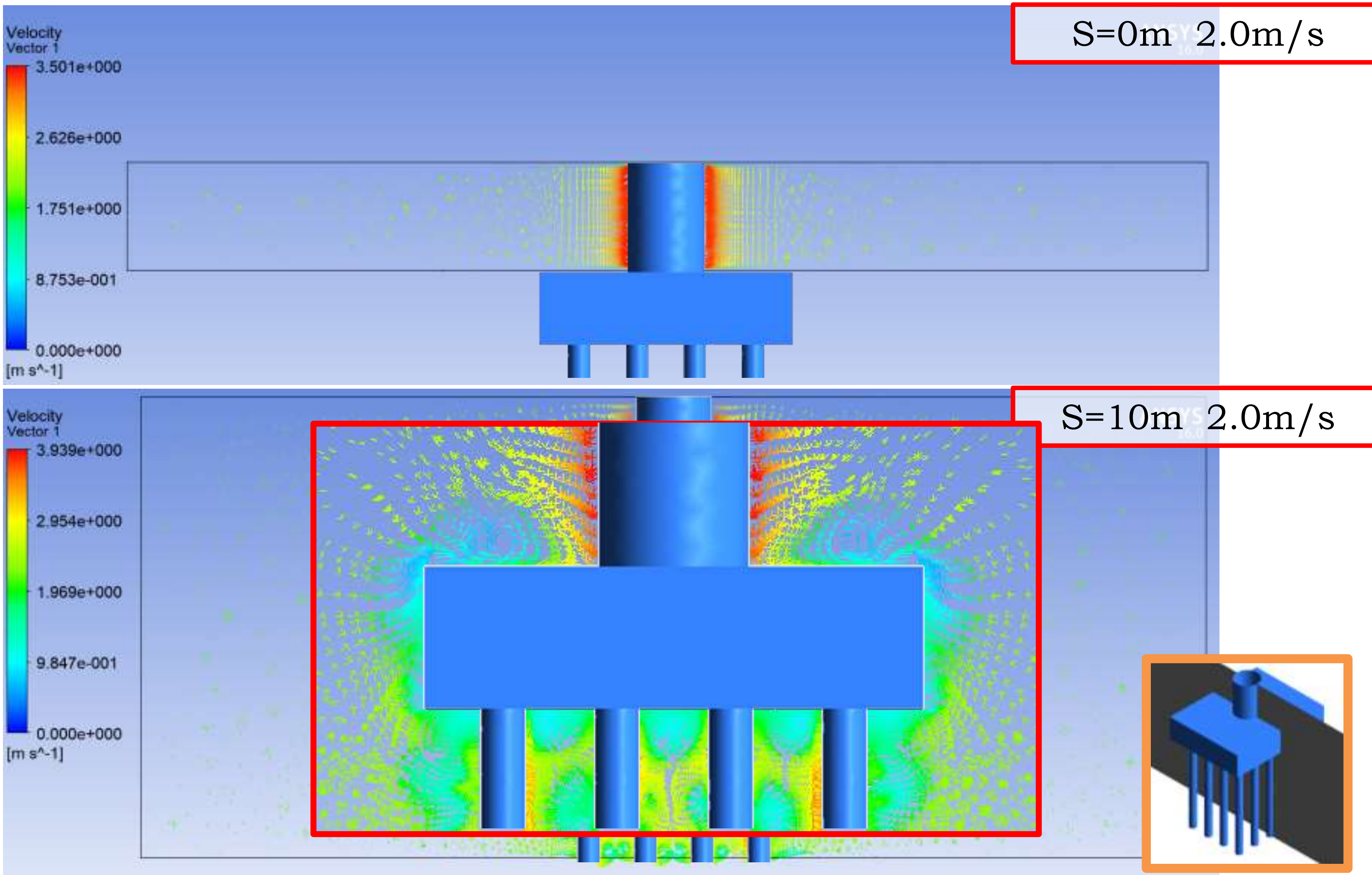





S=0m 2.0m/s
Velocity v
Contour 1
3.467e-001
3.089e-001
2.711e-001
2.333e-001
1.955e-001
1.577e-001
1.198e-001
8.203e-002
4.422e-002
6.404e-003
-3.141e-002
-6.922e-002
-1.070e-001
-1.448e-001
-1.827e-001
-2.205e-001
-2.583e-001
[m s^-1]

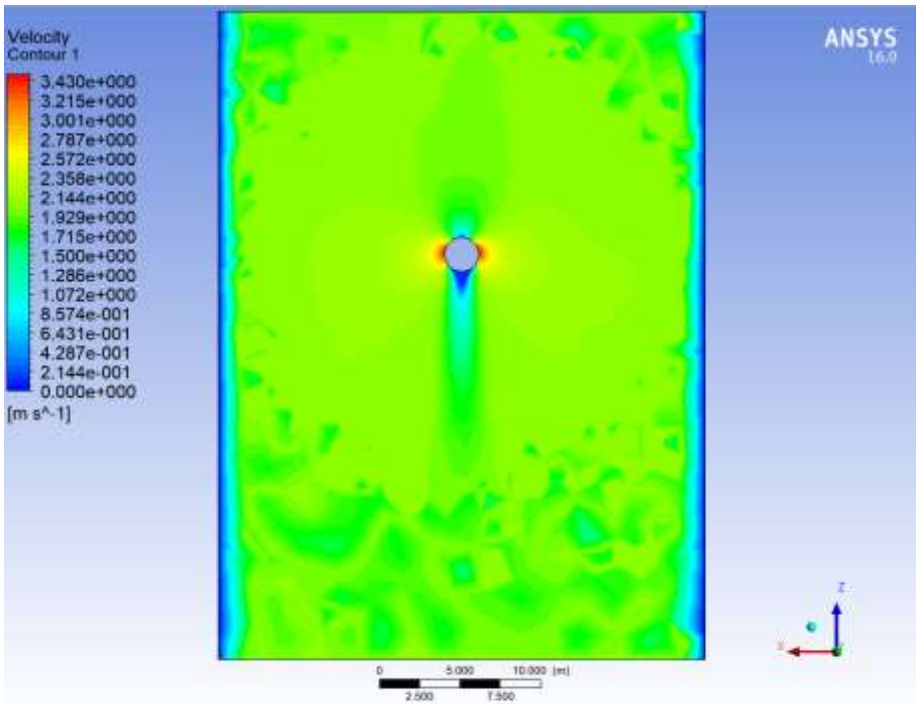

S=10m 2.0m/s
Velocity v
Contour 1
2.082e+000
1.839e+000
1.596e+000
1.353e+000
1.110e+000
8.667e-001
6.236e-001
3.806e-001
1.375e-001
-1.055e-001
-3.486e-001
-5.916e-001
-8.347e-001
-1.078e+000
-1.321e+000
-1.564e+000
-1.807e+000
[m s^-1]

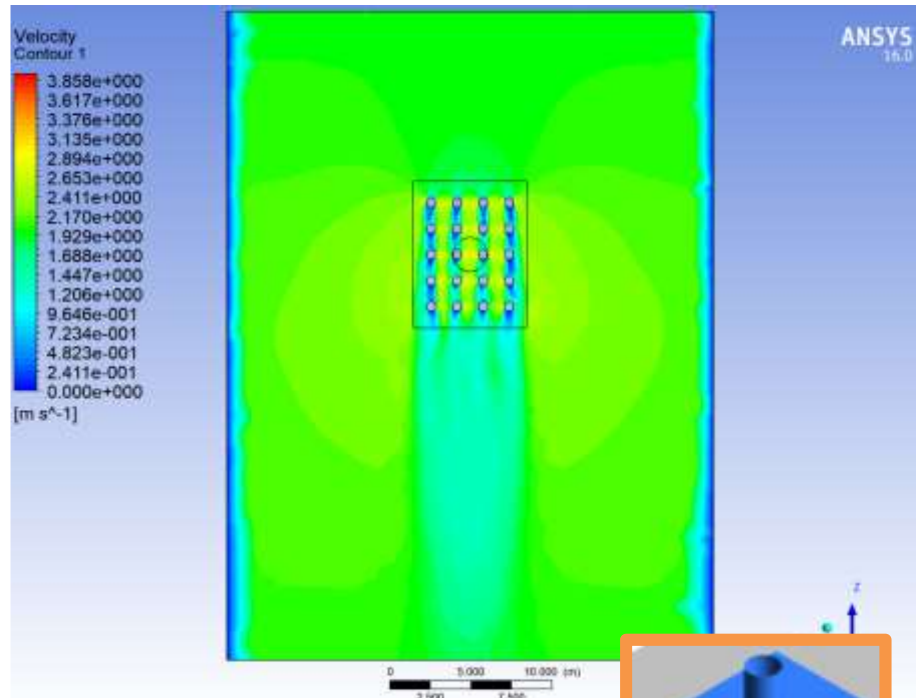
Dynamic Comparison (Tail)

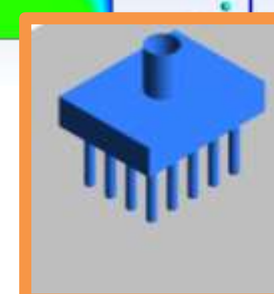


Comparison (Top and Bottom)

S=10m 2.0m/s





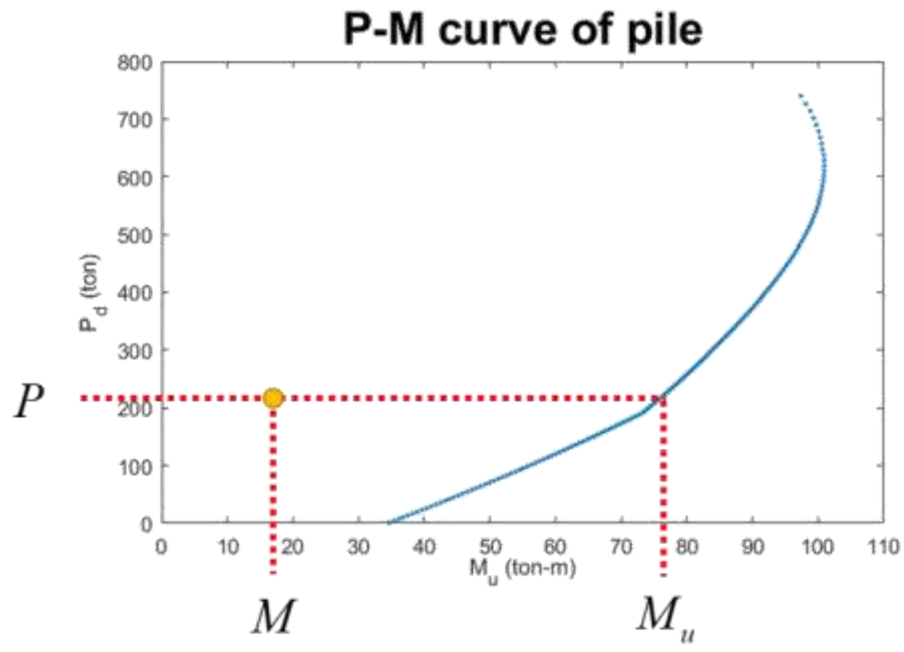


- Ultimate moment (M_u) is found from the P-M curve by the actual axial force collected from the model.

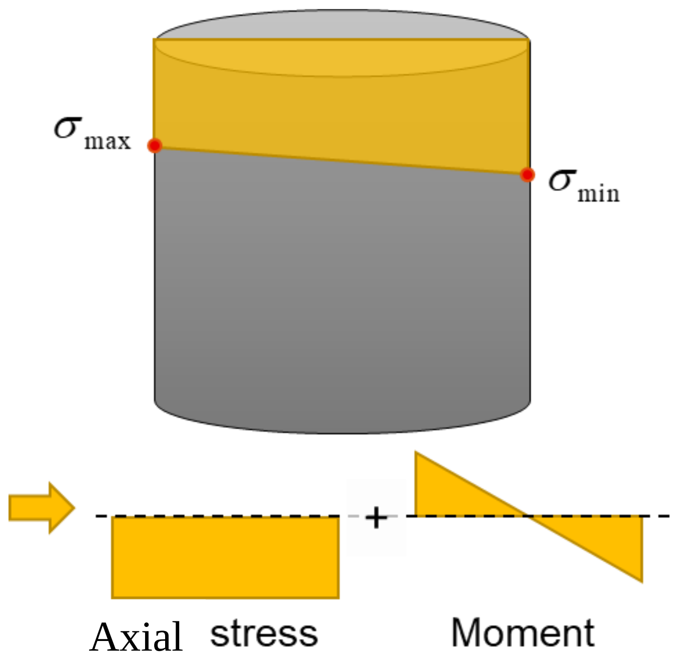
$$FS = \frac{M_u}{M}$$

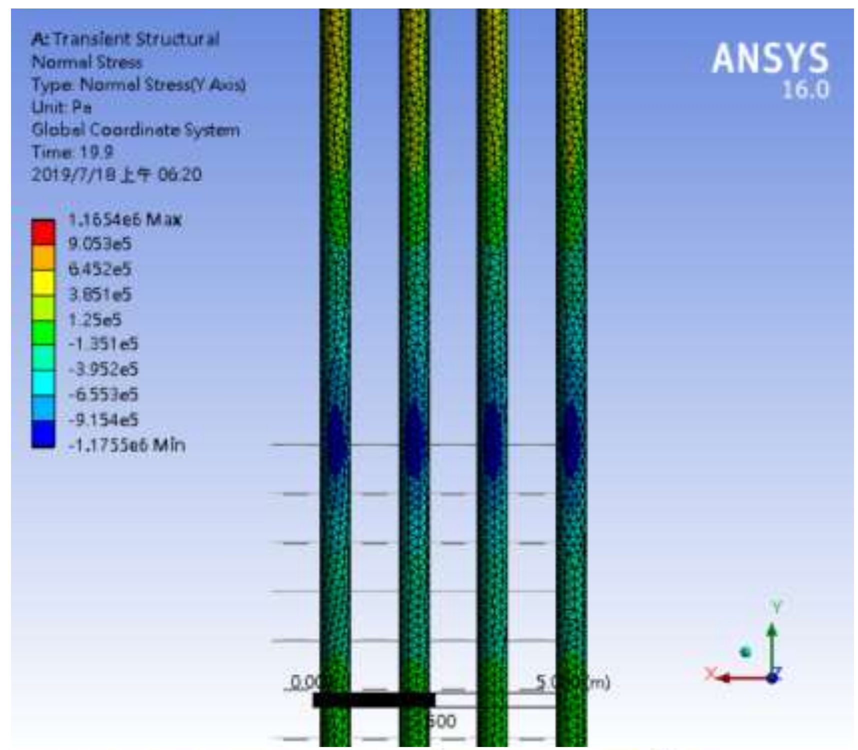
- Allowable displacement (Δ_0) is defined by ultimate moment and axial force.

$$FS = \frac{\Delta_0}{\Delta} \qquad \Delta_0 = 0.2\frac{M_u}{P}$$



- FSI simulation in ANSYS program provides displacement, strain and stress data of element.
- Axial stress and moment at pile is defined by stress data at steady state.





- Scour depth with SF over 3.0 and 2.0 are defined as alert and action level through extrapolation method.

SF of ultimate moment

	0.5	1	1.5	2	2.5	3
0	-	-	-	-	-	-
2	-	-	-	-	-	-
4	927.91	1109.84	418.27	240.74	166.56	116.02
6	525.14	288.71	141.33	85.78	56.14	39.07
8	350.64	111.06	65.45	41.25	25.95	18.05
10	256.33	52.93	36.02	23.38	14.27	9.92
12	198.44	28.89	22.11	14.70	8.75	6.08
14	159.82	17.31	14.64	9.93	5.79	4.02
16	132.50	11.11	10.24	7.07	4.04	2.81
18	112.30	7.52	7.47	5.24	2.95	2.05
20	96.86	5.30	5.64	4.01	2.22	1.54
22	84.73	3.86	4.37	3.14	1.72	1.20
24	74.99	2.89	3.46	2.52	1.36	0.95
26	67.02	2.22	2.79	2.05	1.10	0.76
28	60.39	1.73	2.29	1.70	0.90	0.63
30	54.82	1.38	1.90	1.43	0.75	0.52

SF of allowable displacement

	0.5	1	1.5	2	2.5	3
0	-	-	-	-	-	-
2	-	-	-	-	-	-
4	5546.53	2899.62	1702.79	1163.74	845.98	615.63
6	1542.06	758.90	458.49	308.06	215.92	156.74
8	621.83	293.18	180.73	119.97	81.94	59.38
10	307.42	140.20	87.79	57.73	38.65	27.97
12	172.88	76.73	48.66	31.76	20.91	15.12
14	106.27	46.09	29.55	19.16	12.44	8.99
16	69.71	29.64	19.18	12.37	7.94	5.73
18	48.07	20.08	13.10	8.41	5.34	3.85
20	34.46	14.18	9.32	5.95	3.74	2.70
22	25.51	10.34	6.84	4.35	2.72	1.96
24	19.38	7.76	5.16	3.27	2.03	1.46
26	15.05	5.95	3.99	2.52	1.55	1.11
28	11.91	4.66	3.14	1.98	1.21	0.87
30	9.58	3.71	2.51	1.58	0.96	0.69

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- Fluid-solid interaction simulation was implemented by ANSYS on a scaled pier test simulation, and is applied to practical bridge.
- Among three boundary conditions, scour depth and flow velocity influence structure displacement more then water level.
- Structure displacement at pile top is significantly larger when fluid dynamic impact is considered.
- Two safety factors are proposed to support the alert and action level for bridge health monitoring.

Thanks for your attention!