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Large Deformation Analysis of Waterfront Structure Port of Kobe during Hyogo-Ken Nanbu Earthquake by using 3D Nonlinear Parallel FEM

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SUMMARY:
This paper is concerned on the analyzing of large deformation of the waterfront structures, i.e. gravity caisson quay wall type, on the Port of Kobe by using three-dimensional nonlinear parallel finite element method. The analytical results of a corner part of the Port of Kobe show that the multi-directional shear increases the pore water pressure excessively and, consequently, reduces the frictional resistance on the beneath of the walls. Reducing frictional resistance at the beneath of the walls makes the walls easily to move due to inertia forces acting in the quay walls. As the quay walls move toward the seawater area, the backfill soils then fail and the stiffness of the soil layer was reduced. As a consequence, the pore water pressure was increased. The sequence of the quay walls movement was affected by the pore water pressure responding in an isotropic manner, which is effectively inspected by the three-dimensional analysis.

Keywords: 3D nonlinear FEM, parallel computation, saturated soil layers-civil structure interaction problem

1. INTRODUCTION

The gravity caisson quay walls structures construct as the waterfront structure in the port area often damage during great earthquake. The example is most of quay walls constructed in the Port of Kobe were damaged by the Hyogo-ken Nanbu earthquake on January 17th, 1995. These quay wall structures were moved laterally toward the seawater area and settled in a few meters (Madabhushi, 1995, Ministry of Transport, 1997). The damaged of these waterfront structures are indicating the complexity of the interaction problem between the saturated soil layers and the civil structures. The source of complexity comes from the dynamic response of the saturated soil layers where the soil grains and the pore water interacts each other. An accurate estimation of the dynamic responses of the quay wall and the saturated soil layers behind and beneath of the quay walls, including their interaction, is required to know the causes of the damage of the port facilities such as is located in the Port Island, Kobe.

Analyzing the complex interaction problem such as is mentioned above by using three-dimensional finite element method over large interest domain on a single processor machine, however, often exceeds the available computer capacity. The parallel computation algorithm based on the Domain Decomposition Method has been developed by authors to overcome its limitation (Kawamura and Tanjung, 2002 and Tanjung, 2010). For a case of study, a corner part of Port of Kobe was analyzed and the analytical results were compared to field observation of the damaged of quay walls on the Port of Kobe after Hyogo-Ken Nanbu earthquake, 1995.

2. PARALLEL FINITE ELEMENT MODEL AND ITS NUMERICAL SOLUTION

Port of Kobe is located in artificial island of Port Island, Kobe, Japan. The island was constructed within period of 1966 and 1981 for the first stage, and the second stage was started to reclaim in 1986.

Up to now about 755 ha of the port area have been reclaimed (Yang, 2000). The reclaimed land is contained several layers decomposing of the soils and the stones. The blocks of gravity caisson type of quay wall were constructed as waterfront structures. For an analytical study purpose, a corner part of the Port of Kobe, as shown as dark area in Figure 1, has been chosen as the finite element model. The dimensions of the finite element model are 276 meters long, 240 meters wide and 48 meters depth. The model was meshed into more than 12000 of 8-node brick isoparametric elements and resulting more than 50000 degrees of unknowns. The model was partitioned into 14 subdomains and was solved by using 14 individual processors in the SGI Origin/2000 machine. Partitioning of the meshed model is shown in Figure 2.

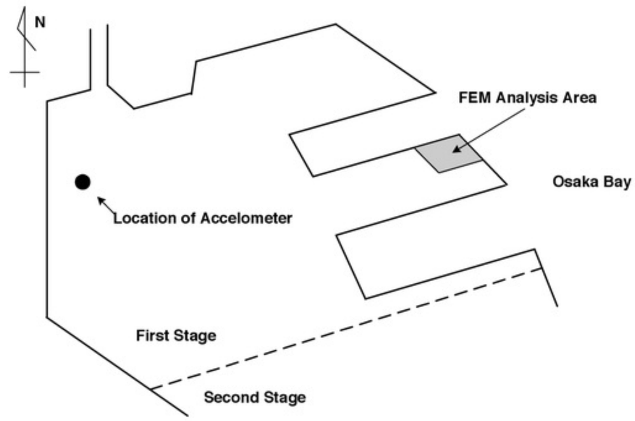


Figure 1. Site Map of Port Island, Kobe

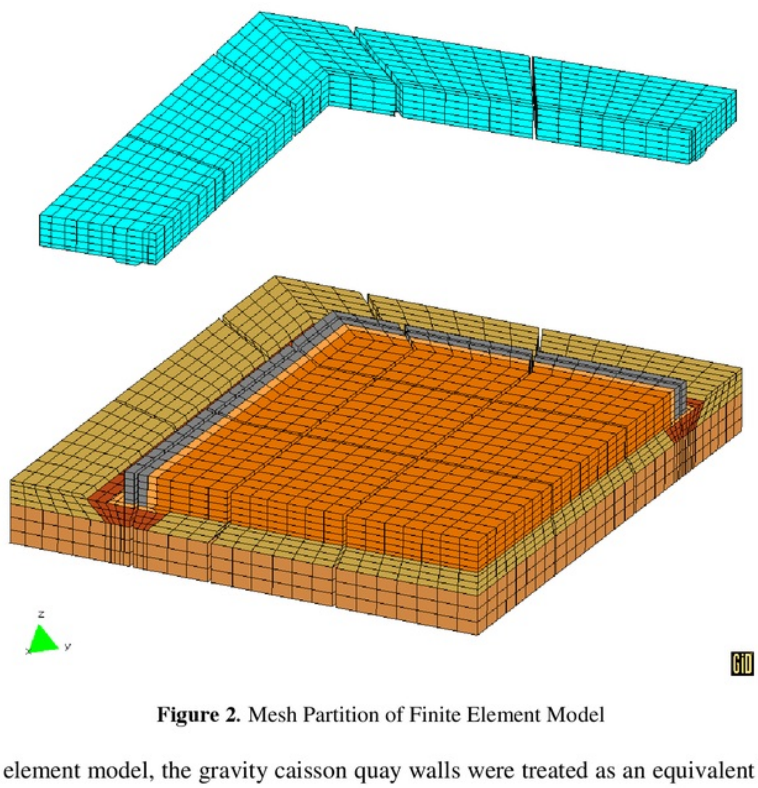


Figure 2. Mesh Partition of Finite Element Model

In this finite element model, the gravity caisson quay walls were treated as an equivalent homogenous solid material and stress-strain relation was assumed to follow the linear elastic response with small strain amplitudes. The material properties for the gravity caisson quay walls are given in Table 1. The soil layers behind and below the quay walls were idealized as a two-phase system coupling of the soil skeleton and the pore water. The stress strain relation for the soil skeleton was represented by the simplification of the bounding surface plasticity model. Detail formulation of its plasticity model has been described by authors in references Kawamura and Tanjung (2002) and Tanjung (2010). This simplified bounding surface plasticity model has 8 parameters to be determined for a particular soil type. These parameters defining the soil layer properties were determined using the standard tests results as were reported Ministry of Transport (1997) for the soil layers located in the Port Island. These parameters, furthermore, were compared to the works of Been (1991) and Wolf-Crouch (1994). The values of these parameters are tabulated in Table 2 for the soil layers marked in the circled number shown in the cross section of the finite element model in Figure 3.

The joint surface elements, i.e. two-dimensional isoparametric element, were introduced to represent the interaction between quay walls and the soil layers. The joint surface elements were also placed between the soil layers as interfaces between these soil layers. Formulation of this joint surface element was derived based on worked of Beer (1985) and Toki (1981) to represent the traction force and relative displacement behaviour on the surface of the joint surface element. This traction force and the relative displacement are evaluated in the normal and tangential directions to the surface of the joint surface element. The parameters for defining the joint surface element properties were collected from several sources such as were reported by Beer (1995), Toki (1981) and Hazarika and Matsuzawa (1997). The values of these parameters are listed in Table 3 for the joint surface element in the boxed number in Figure 3.

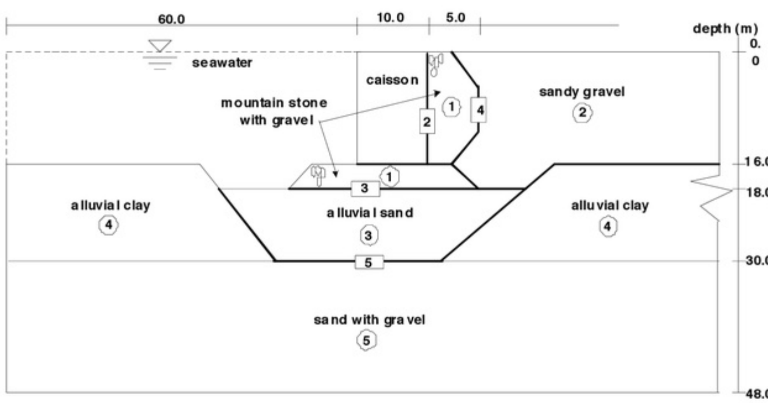


Figure 3. Typical Cross-section of the Finite Element Model

For the seawater, the hydrodynamic affect was approached by considering the displacement the seawater as the unknown as was proposed by Wilson and Mehdi (1983). The equation of motion for the seawater was derived based on the total fluid energy of the fluid movement, the potential energy on the surface wave and the kinematics energy affected by velocity of the wave. In their proposed method, the fluid strain energy is considered based on the linear strain-displacement relation and associated with the compressibility of the fluid. The method involves the introduction of the 'constrain' of zero fluid rotation at the integration point of a fluid element. To eliminate an increment of the fluid stiffness due to high order integration, the method uses reduced integration point to produce a single element fluid 'stiffness' matrix. Finally, the method has been become easily suited into developed parallel finite element code, since the displacement of the seawater was treated as the unknown in the equation of motion of the seawater domain. The material properties for the seawater elements are only bulk modulus of the water K_f and a non-dimensional multiplier constant for defining the rotational bulk modulus of the water $_r$. A value of bulk modulus of the water K_f was taken as 2.08 x 10^6 kN/m^2 and a value of $_r$ has been recommended by Wilson and Mehdi (1983) as 100.

Except for the upper surface of the model, both of soil skeleton and the pore water were not allowed to move outward on the boundaries of the model. The pore water pressures on the upper surface of the model were kept equal to zero during the analysis. The surface wave of the seawater was enforced by their potential energy such that the hydrodynamic pressures remain constant even for large vertical movement. The model was subjected to three components of ground motion recorded by an accelerometer at the depth of 48 meters below the surface of the Port Island. A location of the accelerometer is marked as a filled circle in Figure 1. The accelerations of these ground motions are plotted in Figure 4.

Table 1. Material Properties of Caisson Quay Wall

Property	Symbol	Unit	
Elastic Shear Modulus	G	kN/m^2	2.6×10^6
Poisson's Ratio			0.25
Density	$_d$	kN/m^3	17.0

Table 2. Material Properties of Soil Layers

Property	Symbol	Unit	Layer 1	Layer 2	Layer 3	Layer 4	Layer 5
Effective frictional angle	$_{cr}$	degree	33	31	32	38	35
Slope of isotropic consolidation line			0.035	0.06	0.02	0.25	0.13
Slope of elastic rebound line			0.004	0.0021	0.0026	0.05	0.015
Parameter of shape of elliptic	R		2.25	2.25	2.25	2.25	2.25
Elastic nucleus factor	s_e		1.0	1.0	1.0	1.0	1.0
Hardening shape factor	h_{c1}/h_{c2} h_{e1}/h_{e2}		0.1/0.001 0.1/0.001	0.03/0.002 0.03/0.002	0.03/0.001 0.03/0.001	0.04/0.1 0.04/0.1	0.03/0.1 0.03/0.1
Initial void ratio	e_{in}		0.5	0.35	0.392	1.4	0.5
Poisson's ratio			0.25	0.32	0.342	0.33	0.334
Bulk modulus of granular soil	K_g	kN/m^2	4.0×10^7	4.0×10^7	3.7×10^7	2.3×10^7	3.8×10^7
Bulk modulus of water	K_f	kN/m^2	2.08×10^6	2.08×10^6	2.08×10^6	2.08×10^6	2.08×10^6
Density of saturated soil		kN/m^3	27.0	26.0	23.0	27.0	26.0
Density of water	$_f$	kN/m^3	10.0	10.0	10.0	10.0	10.0
Coefficient of permeability	k	m/s	1.0×10^{-2}	1.0×10^{-2}	1.2×10^{-3}	1.2×10^{-7}	7.0×10^{-5}

Table 3. Material Properties of Joint Surface Elements

Property	Symbol	Unit	Surface 1	Surface 2	Surface 3	Surface 4	Surface 5
Normal Stiffness	k_n	kN/m^3	1.0×10^7	1.0×10^6	1.0×10^6	1.0×10^6	1.0×10^6
Shear Stiffness	K_s	kN/m^3	2.5×10^3	1.6×10^4	1.2×10^5	1.2×10^5	0.75×10^4
Friction Angle		degree	38	35	35	35	36
Hardening Parameter	h		0.0001	0.01	0.01	0.01	0.01

The numerical solution of the equation of motion in current parallel finite element was obtained by integrating the equation using Hilber- method in time domain with constant time step of 0.005 second, 15 seconds time excitation, damping ratio 5% and Hilber- parameter -0.25. The iterative procedures of the modified Newton-Raphson method were applied to solve the nonlinear responses on each time step. Indeed, in the parallel finite element algorithms, the analysis was conducted by allocating the blocks of the computations into several individual processors and most of these computations were performed in the subdomain basis without interprocessor communication. The Domain Decomposition Method was used to partite the whole domain of the analytical model into several non-overlapping subdomains. The continuity condition on interface of subdomains was enforced by introducing the traction forces on these interfaces and was iteratively solved by using the Conjugate Gradient method. The interprocessor communication such that the data can be exchanged from one processor to others, was taking apart when solving this continuity condition. In fact the exchanged data significantly affects the parallel computing performance, since the interprocessor communication will delay the calculation works during analysis. To overcome this situation, the interprocessor communication based on the hypercube networking was applied in this study (Kawamura and Tanjung, 2002 and Tanjung, 2010).

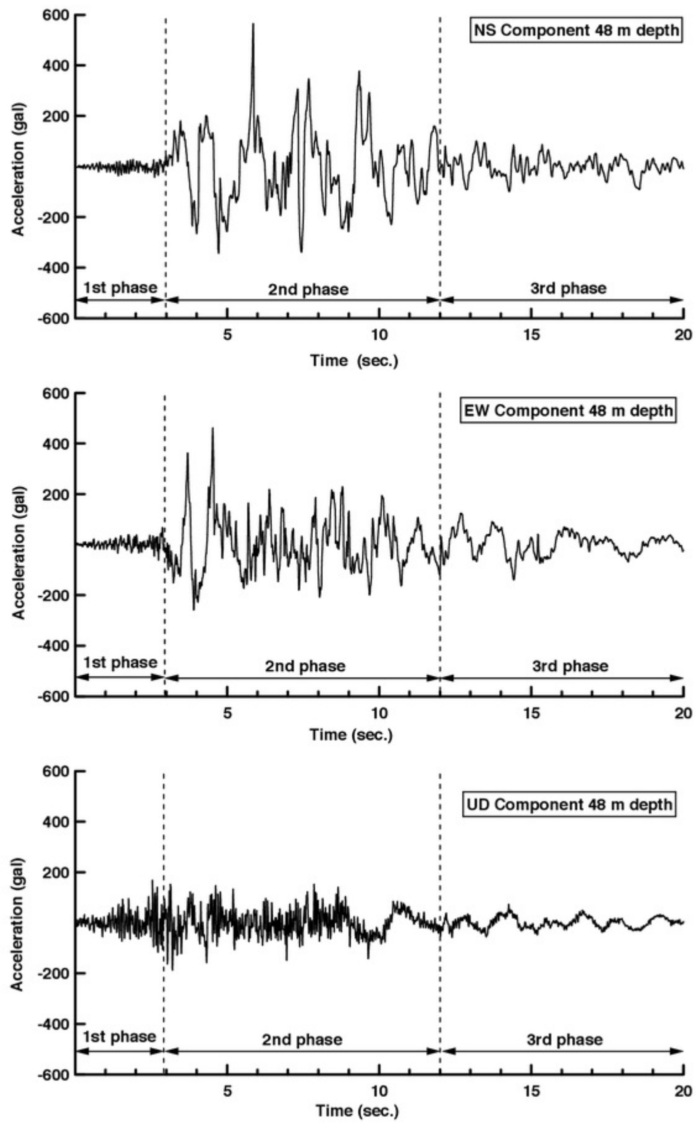


Figure 4. Acceleration Recorded at Port Island during 1995 Hyogo-Ken Nanbu Earthquake

3. ANALYTICAL RESULTS AND DISCUSSION

Figure 5 shows the computed deformation of finite element model subjected to multi directions ground motion of the Hyogo-Ken Nanbu earthquake, 1995. The typical lateral movement and settlement time history for north and east side of the gravity caisson quay walls are plotted in Figure 6. These graphs are plotted based on the responses of quay walls on the nodes A and B as are shown in Figure 5. The negative values of the lateral movement and the settlement correspond with the displacements toward the seawater and downward, respectively.

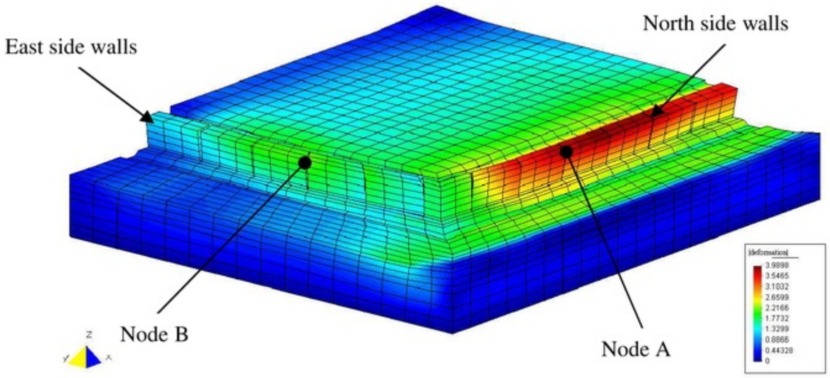


Figure 5. Deformation of the Finite Element Model after 10 seconds Excitation

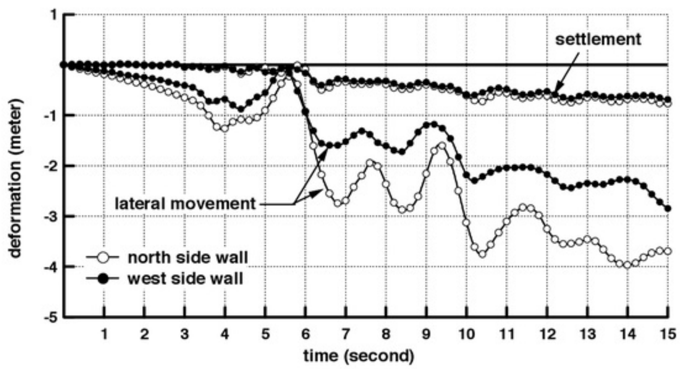


Figure 6. Lateral Movement and Settlement Time History of the Gravity Caisson Quay Walls

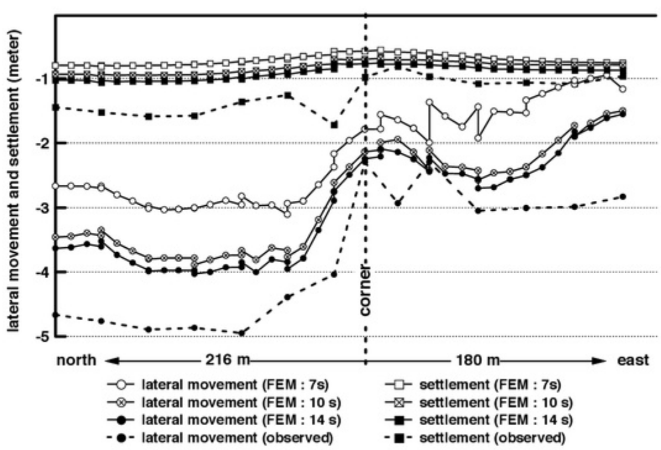
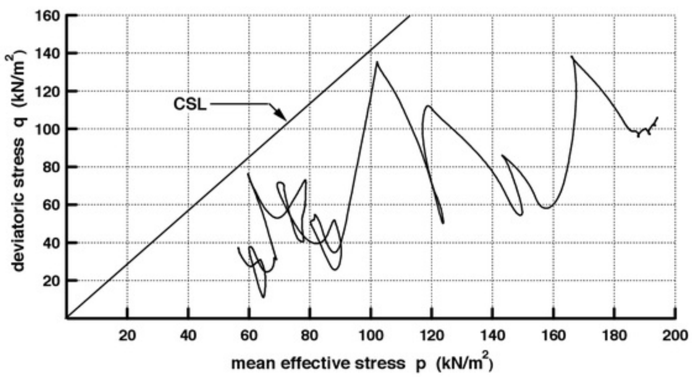
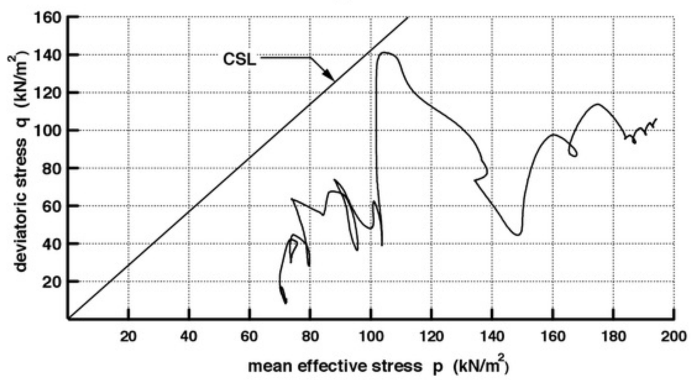


Figure 7. Sequence of Lateral Movement and Settlement of the Quay Walls

The maximum lateral movement of the walls on the north and east sides are about four meters and about three meters, respectively and the settlement is less than one meter. A good agreement has been obtained when the analytical results in this study are compared to the field observation of movements of quay walls after Hyogo-Ken Nanbu earthquake, reported by Ministry of Transport (1997), on the Port of Kobe. The comparison of these results is plotted in Figure 7. The field observation had shown that the lateral movement on the north and east sides about five meters and three meters, respectively, and settlements about one and half meters and one meter, respectively.



(a)



(b)

Figure 8. The Effective Stress Path, (a) Beneath North Wall (b) Beneath East Wall

The concurrent of the large movements of the quay walls are begin after 5 seconds excitation. Multi-directional base excitation induces the multi-directional shear stress in the saturated soil layers and increasing the pore water pressure excessively. As the consequently, the frictional resistance on the beneath of the quay walls becomes reducing. The reduction of the frictional resistance on the beneath of quay walls after 5 seconds excitation makes the quay walls easily to move due to the inertia forces in the quay walls. When the quay walls start to move, the progressive failure of the quay walls is begun. Lateral movement of the quay walls and base excitation causes the pore water pressure significantly increasing in isotropic manner and at the same time the stiffness of the saturated soil layers are reducing. Reduction of the stiffness of these saturated layers makes the saturated soil layers loss their bearing capacity, especially at the beneath of the quay walls. Reduction of the stiffness the saturated soil layers are clearly shown in the effective stress path beneath of the quay walls in Figure 8, i.e. the mean effective stress significantly reduces and the deviatoric stress going to critical state line.

4. CONCLUSIONS

The three-dimensional parallel finite element algorithm has been successfully applied to analyze the cause of the damaged of the waterfront structures in the Port of Kobe during Hyogo-Ken Nanbu earthquake, 1995. A good agreement was achieved when the calculated large movements of the quay walls in this analytical study are compared to the field observation results after Hyogo-Ken Nanbu earthquake, 1995. Based on this analytical study may be concluded that the progressive failure of the quay walls were initially caused by increasing the pore water pressure which is induced by multi-directional shear stress in the saturated soil layer beneath the quay walls. Increasing the pore water pressure, then reduce the frictional resistance on the beneath of the quay walls, makes the quay walls are easy move by their inertia force. Simultaneous lateral movement and base excitation build up high excess pore water pressure and consequently reduce the effective stress in the saturated soil layers, which mean the saturated soil layers loss their bearing capacity.

REFERENCES

Been, K. at. al. (1991), The Critical State of Sands, *Geotechnique*, **Vol. 41**, No. 3, pp. 365-381.

Beer, G. (1985), An Isoparametric Joint/Interface Element for Finite Element Analysis, *Int. Journal Num. Meth. Engg*., **Vol. 21**, pp.585-600.

Crouch, R. S. and J.P. Wolf (1994), Unified 3D Critical State Bounding Surface Plasticity Model for Soils incorporating Continues Plasticity Loading Under Cyclic Path, Calibration and Simulation, *Int. J. Num. Anal. Met*., Geomech. **Vol. 18**, pp. 759-784.

Kawamura, M., and Tanjung, J. (2002), 3D Nonlinear Parallel FEM Analysis for Seismic Earth Pressures of Saturated Soil Layer, *Journal of Structural Engineering/Earthquake Engineering, JSCE*, **Vol 19** No.2, pp 199s-129s.

Madabhushi, S.P.G. (1995), Strong Motion at Port Island During the Kobe Earth-quake, Research CUED/D-SOILS/TR285, Cambridge University.

Ministry of Transport (1997), Damage to port and port-related facilities by the 1995 Hyogo Ken Nanbu Earthquake. The Port and Harbour Research Institute, Japan.

Tanjung, J. (2010), 3D Nonlinear Parallel FEM for Analyzing Dynamic Response of a Large-Scale Saturated Soil Layers-Civil Structures Interaction Problem (Part I: Formulation and its Numerical Solution), *Jurnal Teknik Sipil ITB*, **Vol. 17** No. 2, pp. 81-90.

Toki, K. at.al. (1981), Separation and Sliding Between Soil and Structure During Strong Ground Motion, *Journal of Earthquake Engineering Structural Dynamics*., **Vol. 9**, pp. 263-277.

Wilson, E.L. and Mehdi, K. (1983), Finite Elements for the Dynamic Analysis of Fluid-Solid Systems, *Int. J. for Num. Meth. Engg*., **Vol. 19**, pp.1657-1668.

Yang, J., et. al. (2000), Nonlinear Site Effects on Strong Ground Motion at a Reclaimed Island, *J. Can. Geotech*., **Vol. 37**, pp. 26-39.

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