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Application of 3D non-linear dynamic soil-structure interaction analysis in practical seismic design

Application de l'analyse d'interaction dynamique sol-structure non linéaire 3D dans la conception sismique pratique

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ABSTRACT: This paper presents the application of advanced numerical simulation techniques for Dynamic Soil-Structure Interaction (DSSI) analyses in practical design. The selected real project examples include a multi-span bridge, a large LNG tank, a tall building, an underground structure and an offshore wind turbine. The common principles and procedures, applicable to the DSSI analysis of different structures, are explained. Besides sharing the key design experiences, the benefits of undertaking dynamic non-linear three-dimensional time-history analysis in practical design are highlighted. It is shown that the use of advanced numerical simulation techniques can eliminate the need for unrealistic simplified assumptions often adopted in conventional approaches. They can help to more accurately capture the actual behaviour of the system subjected to earthquake loading, which often results in considerable cost saving while also ensuring a safe design.

RÉSUMÉ : Cet article présente l'application de techniques de simulation numérique avancées pour les analyses d'interaction dynamique sol-structure (DSSI) dans la conception pratique. Les exemples de projets réels sélectionnés comprennent un grand bâtiment, un pont à travées multiples, un grand réservoir de GNL et une structure souterraine. Les principes et procédures communs, applicables à l'analyse DSSI des différentes structures, sont expliqués. Outre le partage des principales expériences de conception, les avantages de l'analyse dynamique non linéaire en trois dimensions de l'histoire du temps dans la conception pratique sont mis en évidence. Il est démontré que l'utilisation de techniques de simulation numérique avancées peut éliminer le besoin d'hypothèses simplifiées irréalistes souvent adoptées dans les approches conventionnelles. Ils peuvent aider à capturer plus précisément le comportement réel du système soumis à une charge sismique, ce qui entraîne souvent des économies considérables tout en garantissant une conception sûre.

KEYWORDS: seismic soil-structure interaction, numerical simulation, seismic performance, time-history analysis, practical design.

1 INTRODUCTION

The complexity of Dynamic Soil-Structure Interaction (DSSI) problems and unavailability of standard and validated analysis techniques and tools routinely resulted in ignoring or greatly simplifying DSSI effects in conventional design.

The topic of seismic soil–structure interaction has received considerable attention in recent years, where findings from numerous academic studies including analytical approaches, numerical simulations, laboratory tests, development of new soil constitutive models, and physical simulations (i.e., shaking table tests, centrifuge tests) provided invaluable knowledge and insight to the DSSI problem. However, despite significant academic advancement in this area, it has not yet been widely adopted in the industry.

This paper presents the authors' selected recent design experiences on the application of advanced numerical simulation techniques for DSSI analyses in practical design. Initially, common principles and procedures, applicable to the DSSI analysis of different structures, are explained. Project examples have been selected to cover the wide variety of cases where non-linear dynamic soil-structure interaction analysis offered significant benefits to the design. The selected real project examples include a multi-span bridge, a large LNG tank, a tall building, an underground structure, and an offshore wind turbine.

2 INPUT GROUND MOTIONS FOR TIME-HISTORY ANALYSIS

Proper selection and modification of ground motion records is the first step to an appropriate and realistic DSSI analysis. The target response spectrum can either be obtained from code or from site-specific probabilistic seismic hazard assessment (PSHA). Examples of relevant studies are presented in Pappin et al. (2015) and Sze et al. (2019).

Real ground motion records are used whenever possible, which are selected from strong ground motion databases. The major considerations in the selection of ground motion records include:

- The shape of the response spectrum of the ground motion should match the shape of the target spectrum within the range of periods significant to the structural response. The target spectrum can be a site-specific response spectrum derived from Probabilistic Seismic Hazard Assessment (PSHA), or a response spectrum specified in the applicable design code.
- The scaling factor applied to the ground motion to match the target spectrum should be close to unity.
- The distance and magnitude of the ground motion should be similar to those earthquakes contributing most significantly to the seismic hazard of the site concerned. The latter are determined from the de-aggregation of the PSHA results.
- The ground condition at the recording station of the selected time history, usually in terms of the geometric average of the

shear wave velocity over the top 30m of the ground ($v_{s,30}$), should be similar to that of the site.

Without modification, the response spectra of the selected time histories in most cases will not closely match the target response spectrum. The selected time histories are either modified by amplitude scaling or spectral matching. In amplitude scaling, a single scaling factor is applied to the entire time history record to scale up/down the record such that the response spectrum matches the target spectrum within the range of periods significant to the structural response. It is noted that a reasonably close match between the response spectrum of the scaled time history and the target spectrum can only be achieved if the response spectrum of the original time history has a shape similar to that of the target spectrum.

To overcome this limitation, the time histories can be modified by spectral matching technique where both the amplitude and frequency contents are modified such that the response spectrum matches closely the target spectrum over the specified period range. An example of time history modified by spectral matching is shown in Figure 1.

Depending on the scope of the analysis, symmetry of the model, and design concerns, time history records in one direction, two directions, or three directions (two orthogonal horizontal directions and one vertical direction) can be applied to the numerical model. In areas of high seismicity and/or close to active fault, or where the structure has significant vertical dynamic response (e.g., long-span bridge, large tank), vertical ground motion input is often required. The number of time history sets required varies depending on the level of details of the design. A minimum of three sets is generally required for preliminary design. Seven or more sets are often required in a more detailed analysis.

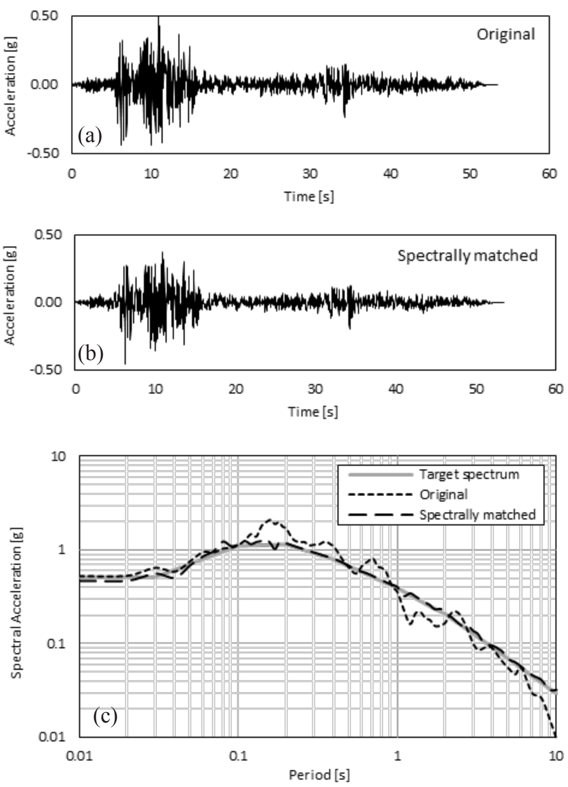

Figure 1. Example of time history modification by spectral matching; (a) original acceleration time history; (b) spectrally matched acceleration time history; (c) response spectrum.

3 CONVENTIONAL ANALYSIS PROCEDURE

In conventional analysis, response spectrum analysis is often carried out for the design of above ground structures. One of the required inputs is a design response spectrum which may be obtained from a design code or site response analysis if site-specific procedure is followed. In a site response analysis, the response (in terms of time histories of displacement, velocity, acceleration, shear stress and shear strain) of a one-dimensional soil column representing the ground profile of the site to an earthquake motion input at its base is calculated.

For the design of underground structures following the ground deformation approach and the assessment of kinematic effects, the lateral free-field ground deformation can be calculated in a site response analysis, which can then be applied in the analysis of the structures to assess the additional forces in the structural members induced by ground deformation. Site response analysis will also be carried out prior to time history analysis for verifying the free-field site response calculated in time history analysis.

4 NUMERICAL MODEL SET UP FOR DSSI ANALYSIS

For the project examples presented here, the general-purpose finite element program LS-DYNA has been used for the DSSI analysis. This program is an explicit dynamic code that runs in the time domain and incorporates both structural and soil non-linearity. It includes a large number of material models that can be used to model the soil and structure, and several contact algorithms that can be used to model the foundation-soil interface. Many of LS-DYNA's capabilities for civil engineering have been developed by Arup (e.g., Willford et al. 2010) and this software has been successfully used by Arup over many years for a wide range of foundation and soil structure interaction problems (i.e., Lubkowski et al. 2000).

The common features of the DSSI modelling in the following project examples are:

- The earthquake ground motions are applied at the base of the models (bedrock) simulating the propagation of earthquake waves from bedrock to ground surface;
- The overall dimensions of the model were chosen to be sufficiently large to ensure capturing of free-field motion in the far-field as well as radiation damping.
- The lateral boundaries are simulated using tied boundaries technique (i.e. all the side nodes at the same height are tied together without relative movement). The correct representation of free-field conditions close to the edge of the model should be checked;
- Non-reflecting boundary conditions are simulated at the base of the model. This artificial boundary condition simulates an infinite half space to prevent the reflection of the outward propagating waves back into the model and contaminating the results;
- The soil elements are modelled as 8-noded solid elements using the non-linear soil material model MAT_HYSTERETIC_SOIL. This model captures the hysteresis of the soil under cyclic loading, where energy dissipation under cyclic response is modelled explicitly (and automatically) as the area enclosed by the shear stress-shear strain hysteresis loops;
- The simulation of structural elements obviously depends on the superstructure type in each project example. The structural elements nonlinear behaviour and damping is simulated depending on the case study;
- The DSSI analysis is performed in a fully coupled manner where main components of the interaction (e.g., soil, foundations, structural elements) are

modelled simultaneously capturing both inertial and kinematic interactions.

The merits of using nonlinear soil models over the simplified equivalent linear methods for DSSI analysis have been discussed in the literature (e.g. Hokmabadi et al. 2014; Xu & Fatahi 2019). The nonlinear soil models can capture the cyclic nonlinear behaviour of the soil more accurately than in equivalent linear methods, where the strain-dependent modulus and damping functions are only taken into account in an average sense to approximate the soil nonlinearity.

Ground investigation including both in-situ and laboratory testing should ideally target to obtain the required soil parameters for dynamic analysis. In the absence of such measurements, published empirical correlations and database of dynamic properties for different soil types and geological conditions are usually adopted in the analysis.

5 PROJECT EXAMPLE 1 – MULTI-SPAN BRIDGE

Arup conducted DSSI analysis for the design of a multi-span bridge located in an area with high seismicity. Three frames (~615m long each) were modelled to account for the impact of the adjacent frames on the seismic response. The masts were sitting on pile groups consisting of 8 steel tube piles with a diameter of ~2.3m. Different water depths along the bridge alignment were considered with depths varying from ~10m to ~40m. The ground profile for analysis consists of soft clay (Marine Deposit) overlying sandy materials and then IGM (Intermediate Geomaterial) at deeper depths. The general configuration of the developed model is shown in Figure 2.

The bridge structural design consists of Friction Pendulum Bearing (FPB) isolators under the bridge deck to reduce the energy transferred to the bridge structure. The time-history analyses were considered necessary for the bridge design as conventional response spectrum analysis (linear analysis) has limitations in capturing the FPB's actual behaviour under the design earthquakes.

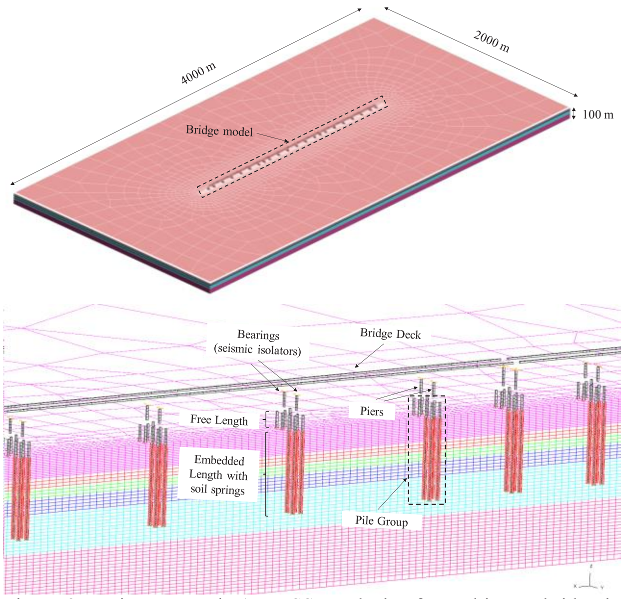

Figure 2. Project Example 1 – DSSI analysis of a multi-span bridge in LS-DYNA: (a) overall model setup; (b) closeup of bridge components modelling (with cut-out).

Furthermore, the time-history analysis, capable of capturing non-linear soil-structure interaction and dynamic pile group effects (i.e., pile-soil-pile interaction), provided valuable information on the performance of the pile foundations in terms of induced seismic loadings and maximum deformations. Figure 3 illustrates the time-history of the bending moments developed at piles head in the first mast under the design earthquake as an example.

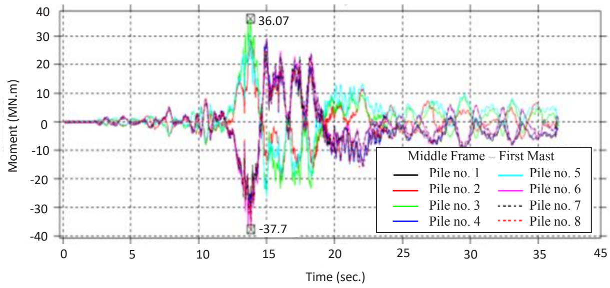

Figure 3. Project Example 1 – bending moments developed at piles head from time-history analysis.

6 PROJECT EXAMPLE 2 – LARGE LNG TANKS

The seismic design of LNG tanks is critically important considering the high consequences of failure given the hazardous nature of the stored product. This project example demonstrates the application of advanced numerical simulation techniques incorporating DSSI for the seismic design of large LNG tanks.

The in-situ ground profile generally consists of 1m of sand fill, which overlies 3m of organic soil, which in turn overlies 10-15m of silty-sandy alluvium deposit with coarse sands towards the bottom. Claystone bedrock, which is underlain by weathered claystone formation of about 5-6m thick, is at a depth of about 22-27m. The design groundwater level is close to the ground surface. Due to the poor ground conditions, different ground improvement techniques (e.g., Deep Cement Mixing, Stone Columns) are evaluated to satisfy the design requirements in terms of bearing capacity and settlement.

The above-ground structure consisted of an inner steel tank inside a secondary concrete outer tank. The inner tank material is 9% Nickel Steel while the outer tank is made of prestressed reinforced concrete. Different tank sizes were investigated with outer tank diameter of ~80-90m and height of ~45-60m. In the numerical model, both the inner and outer tanks were modelled using shell elements (see Figure 4).

The main difference between the seismic design of the liquid storage tanks and the other common civil structures is the hydrodynamic response of the fluid (LNG) contents of the tank. These hydrodynamic loadings, which normally govern the tanks seismic design, is simulated using mechanical analogue in the form of spring-mass system capturing the main vibration modes of the fluid inside the rank:

- Impulsive mode (rigid movement of the liquid);
- Convective mode (sloshing mode);
- Vertical vibration mode.

The hydrodynamic properties of lumped mass are expressed in terms of effective mass, height, period (stiffness), and damping referring to the relevant design codes (e.g., API650, NZSEE 2008). Alternatively, the dynamic fluid-structure interaction can be explicitly modelled in LS-DYNA (Gibson et al. 2015).

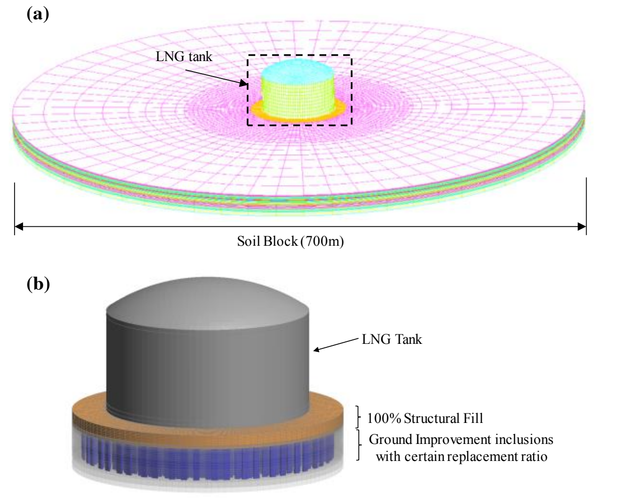

Figure 4. Project Example 2 – DSSI analysis of a large LNG tank in LS-DYNA: (a) overall model setup; (b) ground improvement under LNG tank.

The results of the DSSI analysis can be extracted in terms of accelerations, loads/deformations, stresses/strains, etc. The key outputs from numerical modelling that were critical for the design included: (i) hydrodynamic lumped mass acceleration; (ii) inner tank and outer tank accelerations; (iii) developed stresses for foundation and ground improvement design, and (iv) inner tank sliding and uplift assessment.

Checking of inner tank sliding or uplift over the outer tank concrete base slab during the seismic excitations was an important design requirement in the project. The developed advanced DSSI analysis provided a more accurate assessment in the time domain, rather than just comparing the maximums and minimums in simplified approaches, to ensure the design requirement is satisfied and allow a more realistic assessment in terms of the need for anchoring or other equivalent measures.

Figure 5 shows the horizontal to vertical force ratio of the inner tank over the outer tank concrete base slab for the inner tank sliding check. This ratio can then be checked against the available sliding resistance and the required minimum factor of safety. Please refer to Hokmabadi et al. (2019) for further details.

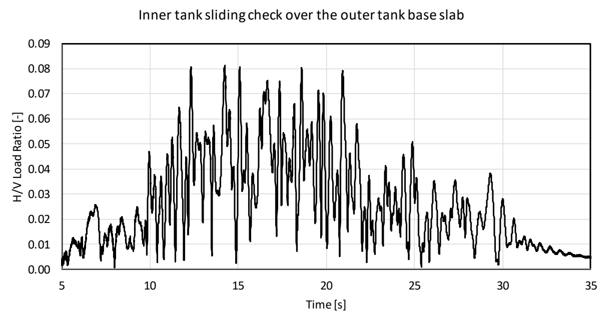

Figure 5. Project Example 2 – Horizontal / vertical force ratio of the inner tank over the outer tank concrete base slab for the inner tank sliding check (Hokmabadi et al. 2019).

7 PROJECT EXAMPLE 3 – TALL BUILDING

The project is a residential 40 storey building with no basement. The building is supported by bored piles with diameter of 1 to 1.8m and maximum length of ~60m. The soil profile consists of ~10m of loose to medium dense sand/silt, which overlies ~6-10m of stiff to very stiff clay. Bedrock is encountered at a depth of ~60m where the end-bearing piles are founded on.

The interaction between soil and pile elements were modelled by nonlinear springs. Each node of a pile beam-column element is connected to a node of the solid soil elements by three spring elements modelling the horizontal (global x and y directions) and the vertical (global z direction) interactions between the piles and the foundation soil. The nonlinear springs include the nonlinear response of soil and the yielding force (passive soil resistance) characteristics.

The superstructure model was created in a separate structural software and imported into LS-DYNA for time-history analysis.

The results of DSSI analysis were fed back to structural design team for design optimisation. It was also used to check and optimise the pile foundation design. Unlike conventional analysis methods, the DSSI time-history analysis could capture the soil nonlinear behaviour and pile group effects under seismic loadings more realistically, thus offering notable design optimisation. The design optimisation was mainly achieved by demonstrating a reduction in base shear and seismic loadings on both structural components and piles through consideration of DSSI effects. Nguyen et al. (2017) provides detailed discussion on the influence of size and load-bearing mechanism of piles on the seismic performance of buildings considering soil–pile–structure interaction.

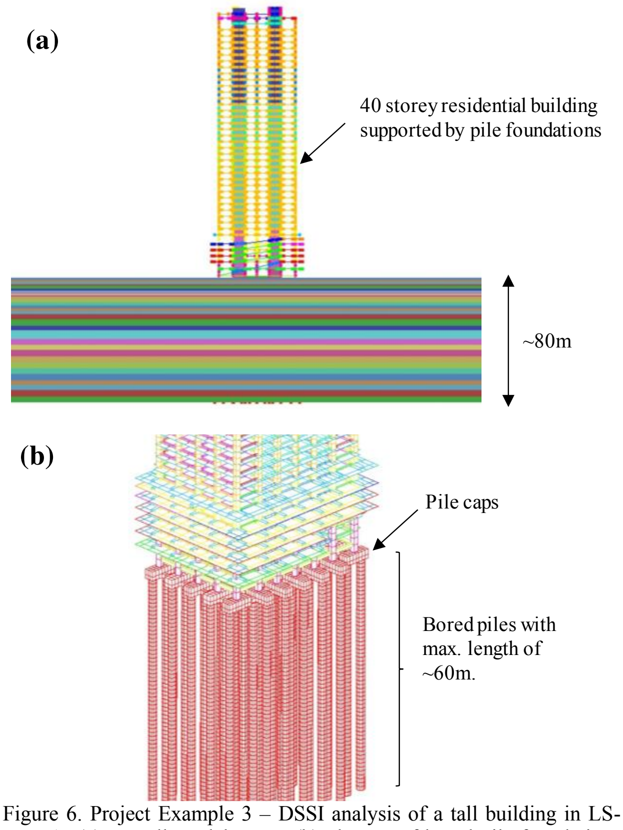

Figure 6. Project Example 3 – DSSI analysis of a tall building in LS-DYNA: (a) overall model setup; (b) closeup of bored pile foundations modelling.

8 PROJECT EXAMPLE 4 – UNDERGROUND STRUCTURE

The analysis involves a 400m long underground railway station box. The primary structure is constructed by the top-down method and consists of two lines of 1.2m thick diaphragm walls and two 1m thick slabs (i.e., the top and bottom slabs). The structure also consists of internal slabs and walls, of varying thickness, that define the line of the railway. The consequent, unused volumes created by these internal walls are filled with mass concrete to counter the buoyancy of the structure.

The ground generally consists of about 10m thick surficial sandy fill materials, which overlay silty marine deposit, which in turn overlay alluvium sand and then completely decomposed granite above the bedrock which is encountered at a depth of about 16.5m. The DSSI model is shown in Figure 7. The overall dimensions of the model are sufficiently large to ensure a free-field condition close to the edge of the model. The ground motion time-history records are applied at the model base as a bi-axial earthquake excitation in the horizontal and vertical directions.

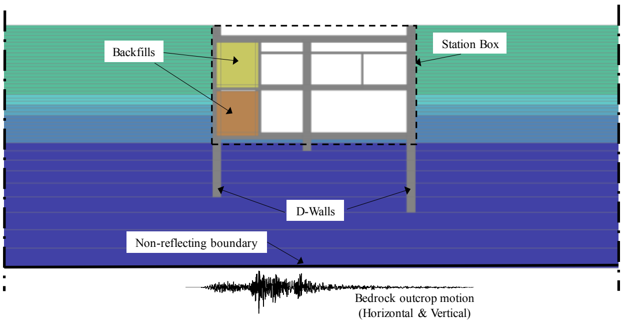

Figure 7. Project Example 4 – DSSI analysis of an of underground station.

This study compares the results of dynamic time-history analysis and simplified pseudo-static analysis following the ground deformation approach (Free et al. 2001) under different conditions including level of ground motion. The conditions under which the simplified pseudo-static method that can be considered sufficient for design purposes are studied. The additional bending moments induced by the design earthquake in the top slab are shown in Figure 8 as example.

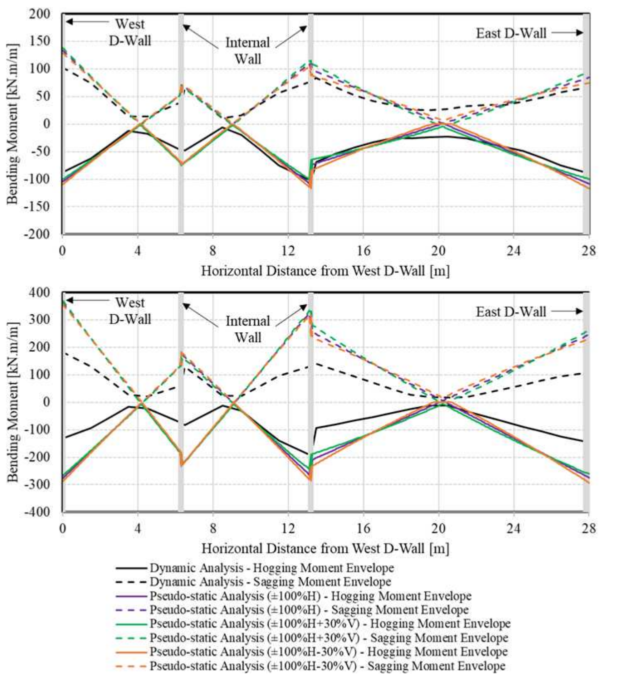

Figure 8. Project Example 4 – Bending moment of top bottom slab (LS-DYNA vs. Plaxis).

Under the considered design earthquake ground motion (PGA = 0.15g for a return period of 1000 years), the results of the time-history analysis compare reasonably well with the results of pseudo-static analysis, albeit with a higher estimation of bending moments at slab/wall joints. The pseudo-static analysis gives less satisfactory results under increased ground motion (twice the considered design earthquake ground motion), especially for the top slab where overestimation of bending moments at slab/wall joints is apparent. The deformation-based pseudo-static finite element method is concluded to be generally appropriate for the seismic design of typical underground structures in regions of low to moderate-seismicity. This eliminates the necessity of more demanding time-history analysis in practice.

9 PROJECT EXAMPLE 5 – OFFSHORE WIND TURBINE

Wind energy production from offshore wind farms has been rapidly growing globally. In recent years, some Asian countries with long shorelines (e.g., Japan, South Korea, Taiwan, etc.) start developing offshore windfarms in seismicity active regions. Some of the geotechnical challenges for offshore windfarm foundation design in emerging Asian market has been discussed by Cheung et al. (2020).

The selection of a suitable and cost-effective foundation type from depends on several factors such as the seabed ground conditions, water depth, turbine size, transportation and installation limitations, etc. Monopiles have been the most popular foundation type followed by jacket foundations. The foundation design of offshore wind turbines normally follows soft-stiff design concept, where the permissible natural frequency for the operation of wind turbine is normally in the range of ~0.2Hz to ~0.35Hz, depending on the turbine size and its manufacturer.

The seismic design codes and guidelines for such novel structures have not been well developed nor validated and there is limited experience on design of offshore wind farms in seismically active regions. Existing seismic design codes are mostly developed for conventional structures and may not be directly applicability to offshore wind turbines (Bhattacharya et al. 2021). As such, the design normally relies on time-history analysis to improve understanding and gain more confidence on the seismic performance of the system.

This project example presents an advanced DSSI in LS-DYNA for seismic design of an offshore windfarm project located in a highly seismic region in East Asia. The wind turbines have a rated capacity of ~10MW supported by steel tube monopiles with an outer diameter of ~9-10m. The general configuration of the developed model is shown in Figure 9.

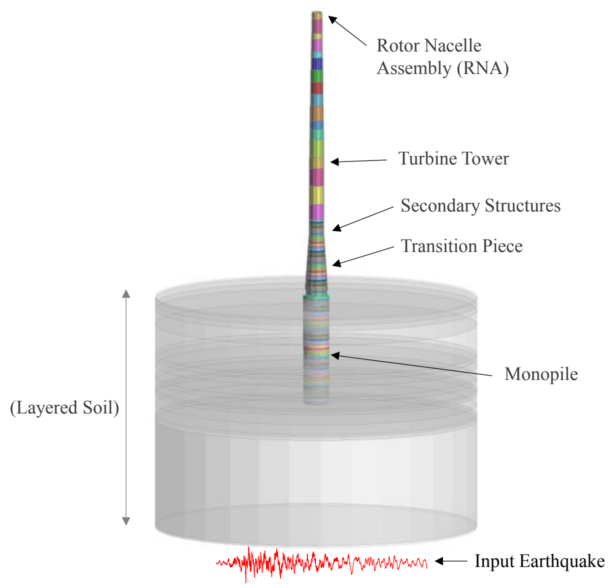

Figure 9. Project Example 5 – DSSI analysis of an offshore wind turbine supported by a large diameter monopile.

The ground profile consists of interbedded layers of sand and clay above the bedrock at a depth of ~55m. The liquefaction study identified sandy soil layers with liquefaction potential under the design earthquake. The time-history analyses were conducted for two cases:

- Total stress analysis with non-liquefied soil.
- Effective stress analysis with liquefied soil.

In the effective stress analysis, the development of excess pore water pressure (PWP) in liquefiable layers was simulated using the SANISAND constitutive soil model. The SANISAND model is an advanced effective stress plasticity model within the framework of critical state soil mechanics and bounding surface plasticity for sands (Taiebat & Dafalias 2008).

The development of excess PWP in different liquefiable zones from effective stress analysis is demonstrated in Figure 10. The excess pore water pressure ratio (r_u), as defined in Eq. 1, can be used as a normalised measure of the excess PWP development in liquefiable zones. The excess pore water pressure ratio exceeding ~0.85% ($r_u > 0.85$) is typically considered as criteria for onset of liquefaction.

$$r_u = 1 - \frac{\sigma'_v}{\sigma'_{vo}} \quad (1)$$

where, r_u is the excess pore water pressure ratio; σ'_v is the effective stress at time r_u is determined, and σ'_{vo} is the initial effective stress.

The results of the DSSI analysis were used to inform the design on the foundation internal forces, lateral deformations (reversable and permanent), and response of the superstructure under seismic loading. The results were also used to validate the assumptions for simplified analysis such as response spectrum analysis and 1D beam-spring models.

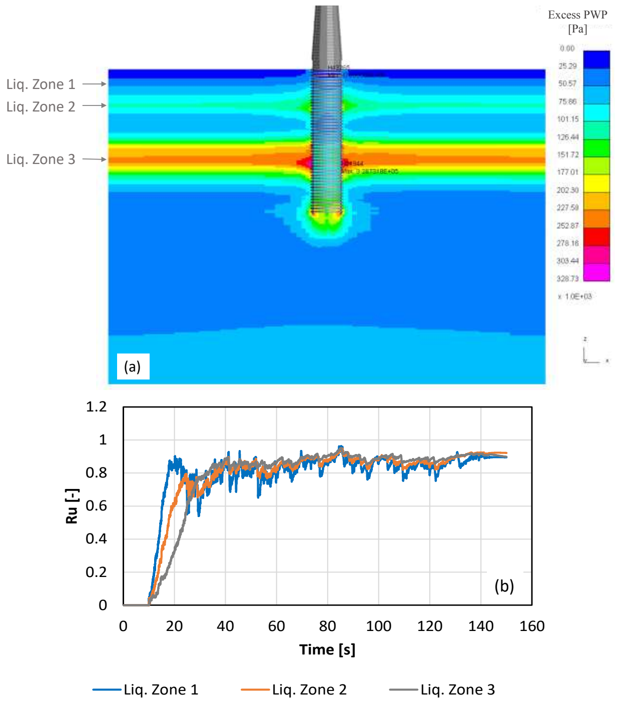

Figure 10. Project Example 5 – Simulation of Excess PWP development in liquefiable layers for effective stress DDSI analysis: (a) Excess PWP contours; (b) Onset of liquefaction at liquefiable zones

10 CONCLUSIONS

The application of advanced numerical simulation techniques for DSSI analyses in practical design was presented through several project examples. The common principles and procedures for undertaking DSSI analysis were briefly explained.

The paper aims to show that while the high computational cost and lack of sufficient technical understanding on seismic behaviour of geo-structures has led to significant simplifications in design in the past, such simplifications are no longer necessary in many practical design cases owing to the insight provided by substantial recent research together with the availability of fast computational tools.

The use of advanced numerical simulation techniques can eliminate the need for unrealistic simplified assumptions often adopted in conventional approaches. They can help to more accurately capture the actual behaviour of the system subjected to earthquake loading, which often results in considerable cost saving while also ensuring a safe design and manageable design risks.

11 REFERENCES

American Petroleum Institute (API) 2007. Welded Tanks for Oil Storage, API 650, *American Petroleum Institute Standard*, Washington D.C.

Cheung A., Hokmabadi A.S., Tang H.P.O. & Yiu J. 2020. Geotechnical challenges for offshore windfarm foundation design in emerging Asian market. *4th International Symposium on Frontiers in Offshore Geotechnics*, Austin, USA.

Free M.W., Pappin J.W., Sze J.M.C. & McGowan M.J. 2001. Seismic design methodology for buried structures. *14th Southeast Asian Geotechnical Conf.*, Hong Kong.

Gibson R., Mistry A., Go J. & Lubkowski Z.A. 2015. Fluid structure interaction vs. lumped mass analogue for storage tank seismic assessment. *SECED Conf. Earthquake Risk and Engineering towards a Resilient World*, Cambridge, UK.

Hokmabadi A.S., Fatahi B. & Samali B. 2014. Assessment of soil–pile–structure interaction influencing seismic response of mid-rise buildings sitting on floating pile foundations. *Computers and Geotechnics*, 55, 172-186.

Hokmabadi A.S., Leung E.H.Y., So M. & Yiu J. 2019. Impact of Soil-Structure Interaction on the Seismic Design of Large LNG Tanks. *HKIE Geotechnical Division Annual Seminar*, Hong Kong, 62-70.

Lubkowski Z.A., Pappin J.W. & Willford M.R. 2000. The influence of dynamic soil structure interaction on the seismic design and performance of an ethylene tank. *12th World Conference in Earthquake Engineering,* Auckland, New Zealand.

Nguyen, Q. V., Fatahi, B. & Hokmabadi, A.S. 2017. Influence of size and load-bearing mechanism of piles on seismic performance of buildings considering soil–pile–structure interaction. *International Journal of Geomechanics*, ASCE, 17 (7), 4017007.

NZSEE. 2008. Seismic Design of Storage Tanks, Recommendations of a NZSEE Study Group on Seismic Design of Storage Tanks. *New Zealand Society for Earthquake Engineering*, Wellington, New Zealand.

Pappin J.W., Koo R.C.H., Jiang H., Kwan J.S.H., Yu Y.B., So M.M.L., Shiu Y.K., Ho K.K.S. & Pun W.K. 2015. A rigorous probabilistic seismic hazard model for Southeast China: a case study of Hong Kong. *Bulletin of Earthquake Engineering*, 13 (12), 3597–3623.

Sze E.H.Y., Leung E.H.Y., Koo R.C.H., So M.M.L. & Pappin J.W. 2019. Geotechnical advances in development of a seismic code for Hong Kong. *Proceedings of the ICE – Geotechnical Engineering*, 172 (1), 87-108.

Taiebat M. & Dafalias Y.F. 2008. SANISAND: Simple anisotropic sand plasticity model. *Int. Journal for Numerical and Analytical Methods in Geomechanics*, 32, 915-948.

Willford M., Sturt R., Huang Y., Almufti I. & Duan X. 2010. Recent Advances in Nonlinear Soil Structure Interaction Analysis using LS-DYNA. *Proc. of the NEA-SSI Workshop, October 6-8,* Ottawa, Canada.

Xu R. & Fatahi B. 2019. Impact of in situ soil shear-wave velocity profile on the seismic design of tall buildings on end-bearing piles. *Journal of Performance of Constructed Facilities, ASCE*, 33 (5).