A NUMERICAL ANALYSIS BASED SUBSTITUTE METHOD FOR SHAKING TABLE TEST IN CONSIDERING OF THE SOIL-STRUCTURE INTERACTION

Y.R. Wang[1], J.W. Dai[2], S.M. Zhan[3] and Y. Jiang[4]

[1] *Ph.D Student, Dept. of Structural Engineering, Institute of Engineering Mechanics, Harbin. China*
[2] *Professor, Dept. of Structural Engineering, Institute of Engineering Mechanics, Harbin. China*
[3] *Master, Dept. of Structural Engineering, Institute of Engineering Mechanics, Harbin. China*
[4] *Master, Dept. of Journal Press in Science and technology , Institute of Engineering Mechanics, Harbin. China*
Email: yanrupiaoyang@163.com

ABSTRACT:

This paper proposes a numerical analysis based substitute method for conducting of the earthquake simulation test on shaking table for high-rise tower structure in considering of the soil-structure interaction, due to the limitation of the load--bearing capacity, the size of the shaking table and the difficulty in simulating both of the soil foundation and its' boundary condition in experimental practice. An off-shore high-rise tower structure is taken as the example for developing of the proposed substitute method. Corresponding 3-D finite element analysis model (model A) with all parts of soil, foundation and the upper structure is developed to simulate the seismic behavior of the entire prototype tower structure in considering of the soil-structure interaction. For avoiding to introduce of the large volume soil in earthquake simulation test practice on shaking table, an equivalent numerical 3-D finite element model (model B) without soil part but with adjusted foundation structure and the same upper structure is developed to obtain the same seismic performance of the upper structure with model A. Series of numerical modal analyses, response spectrum analyses, earthquake time-history analyses are carried out for both of model A and model B. Tentatively Adjusting of both of the constrain condition and the structure of the foundation of model structure B is the key issue of obtaining the same seismic performance of model B with model A. Consequently, both of the expected advantages and possible errors of the proposed substitute method is analyzed in considering of the soil-structure interaction by using the earthquake simulation test on shaking table for high-rise tower structure.

KEYWORDS:
Earthquake Simulation Test, High-rise Tower Structure, Shaking Table, Substitute Method; Soil-Structure Interaction

1. INTRODUCTION

Earthquake, one of the most severe natural disasters, usually causes building damage and casualties; it could make significant lost to the world. As almost of the casualties and losing are due to the structural failure, the study for the earthquake response of the buildings and suitable measurements in design become one of important research projects for technical engineers. The traditional method of seismic design usually based on the rigid foundation assumption. However, the rigid foundation assumption is found to be not accord with the fact along with the accumulation of earthquake disaster data and the further research on seismic performance. The increase of the damping for the structural vibration which due to the interaction of the soil and structure will cause the whole structural system become more flexible, furthermore, the natural vibration period could be extended after then. Hence, the traditional rigid foundation assumption which ignored the interaction of the soil and structure could be more rigid, and the horizontal seismic action on structure is increased subjectively, mostly the design could be conservative but expensive, even though it is accepted by most designers already. However, as the seismic reaction mechanism of complicated structure is unknown, the rigid foundation

assumption could also make seismic action fuzzy and lead to section enlarged and deadweight increased. The structure could be more dangerous caused by the subjectively change of the energy dissipation mechanisms of structure with escapable destroy. In that case, the design with rigid foundation assumption could not only a waste of money but also bring potential dangerous for the structure and the resident. Consequently, it is necessary to consider soil-structure interaction in design processes, especially for increased complex high-rise projects. It is important to study design theories considering soil-structure interaction; moreover, shaking table test is necessary to verify research results, put forward calculation-analysis model, and improve analytical method.

This paper intends to examine seismic response characteristics of high-rise tower, the Star of Weihai, by shaking table test. In the past shaking table test, the soil-structure interaction is realized by soil filled boxes filled. Nevertheless, due to the limitation of the load-bearing capacity, if the soil box is used in the experiment, the engineer's scale could be too small to cause the failure of the assumption. This paper proposes a numerical analysis based substitute method for conducting of the earthquake simulation test on shaking table for high-rise tower structure in considering of the soil-structure interaction. An off-shore high-rise tower structure is taken as example for developing of the proposed substitute method. This substitute method provides an important reference for scientific researchers when carry out the earthquake simulation test on shaking table considering soil-structure interaction, it also bring an effective methodology for complete the shaking table test under limited condition with lower budget.

2. THE THEORY OF THE SUBSTITUTE METHODOLOGY

The substitute methodology could be divided into two steps:

Step one: A 3-D finite element model (model A) considering soil-structure interaction is built using substructure methodologies, integral finite element, or lumped parameter methods by finite element analysis software such as ANSYS, SAP2000, MIDAS, and ETABS. The model is essentially consistent with prototype structure in force state as it considers infrastructure, superstructure, and the effect of soil. This model could exactly reflect load effect of the high-rise tower structure and conduct the structure design. In the substitute methodology, model A is an essential condition to realize the earthquake simulation test on shaking table.

Step two: Another 3-D finite element model (model B) equivalent compared with model A is built by the corresponding software. Model B have the same upper structural with Model A, however, the soil-structure interaction is not simulated by soil box but with the adjusted foundation structure. As the performance of model A and B could be periodicity the same, series of numerical modal analyses, response spectrum analyses, earthquake time-history analyses are carried out for both of model A and model B. Tentatively Adjusting of both of the constrain condition and the structure of the foundation of model structure B is the key issue of obtaining the same seismic performance of model B with model A. The scaled model of model B which is substituted for the scaled model of model A is applied in the earthquake simulation test on shaking table. The seismic performance of prototype structure is reflected by the scaled model of model B.

This paper explains how the substitute methodology is realized by the given high-rise tower structure, the Star of Weihai. Firstly, 3-D finite element software, ETABS9.0.0, is used to build two models: the model considering soil-structure interaction (model A) and the equivalent model (model B). Series of numerical modal analyses, response spectrum analyses, and earthquake time-history analyses are carried out to verify that the scaled model of model B could reflect seismic performance of prototype structure. The details are described as follows.

3. THE APPLICATION OF THE SUBSTITUTE METHODOLOGY

3.1 Engineering Background

The Star of Weihai, an offshore sightseeing tower, is shown in Fig. 1. The tower is located between Weihai and Liugong Island; it is 1500m away from Weihai shore and approximately 2700m away from Liu Gong Island. The Star of Weihai tower, which is a reinforced concrete tower, is situated in the offshore platform with the elements of under turret, the tower body, the turret, and the mast. The height is 285M. The offshore platform structure is reinforced concrete with the size of 55M×55M×7M. There are 81 piles in the under-platform foundation; the diameter of the pile is 2M; the length of the pile ranges from 46M to 60M. The safety grade of the offshore sightseeing tower is Class II; the age limit of structure designed is 50 years; the importance factor is 1.0; the classification of anti-seismic measure is Class III; and the classification of construction site is Class II. The construction form of the sightseeing tower is novel; and its structure is complicated. So the accuracy of estimation for accumulated seismic load is necessary to ensure structure to be safe and economical.

3.2 Establishment of Model

Model A (Fig.2): the 3-D finite element software ETABS9.0.0 is applied to build model A with consideration of the influence of soil, pile foundation, offshore platform, and upper structure. The model is nearly the same with the real structure in force state. Soil-structure interaction is simulated by the constrained spring; that is to say, soil-structure effects are substituted by the spring system. The effect on structures is proportional to the spring distortion. The proportional coefficient K (table 1), which is determined by geological data, is connected with types of soil, physical mechanics condition, and displacement.

Model B (Fig.3): an equivalent 3-D finite element model (model B) with model A for seismic simulation purposes. The model includes the adjusted foundation structure and the same upper structure; and it is used in the earthquake simulation test on shaking table. Series of numerical modal analyses, response spectrum analyses, earthquake time-history analyses are carried out for both of model A and model B. Tentatively adjusting of both of the constrain condition and the structure of the foundation of model structure B are the key issues to obtain the same seismic performance of model B with model A. For the specific case, pile structure of the offshore sightseeing tower changes as follows: the length of the pile is reduced to 26.5M; and the two level restraint boards are added at 9.5M and 17.5M below the lower surface of the offshore platform. The thickness of the level restraint board is 800MM. Although the construction form of pile foundation is changed, upper structure's seismic performance of model B could reflect model A's. That would be proved in the following paragraph.

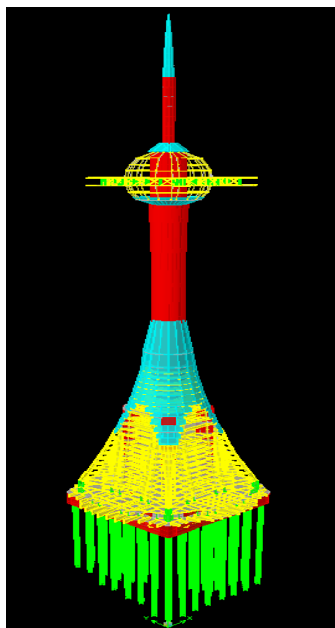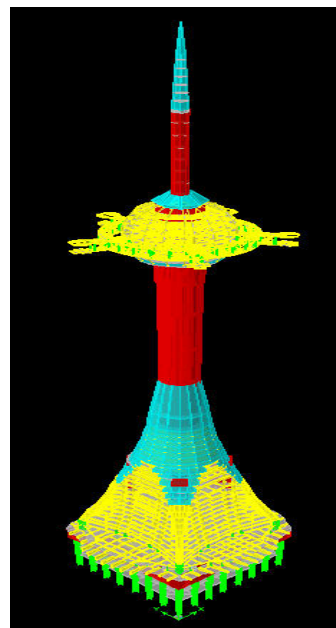| Fig.1 rendering of the star of weihai | Fig.2 model A | Fig.3 model B |

Table 1 The value of proportional coefficient

Serial number	The name of rock soil foundation	The value of K（KN/M^3）
①	low liquid-limit clay	3924
②	high liquid- limit clay	8583.75
③	low liquid limit clay with sand	26835
④	clayey sand	35561.25
⑤	low liquid-limit clay	85837.5
⑥	high liquid limit clay with sand	171675
⑦	strong weathered gneissic granite	392400
⑦1	cataclastic rock	392400
⑧	weak weathered gneissic granite	784800
⑧2	weak weathered leptynite	784800
⑨	weak weathered gneissic granite	4414500
⑨1	weak weathered leptynite	4414500

4 THE VERIFICATION OF THE SUBSTITUTE METHOD

4.1 The Verification by Modal Analysis

In order to analyze structure distortionlessly, the modal analysis is first applied to explain whether the substitute method is feasible. The results of modal analysis are shown in table 2.

Table 2 The result of modal analysis

Orders of model	Cycles of model A /s	Modes of model A	Cycles of model B /s	Modes of model B	The Cycle deviation of model B and model A /s	The cycles ratio of the deviation to model A	The cycles ratio of model B to model A
1	4.39	Y direction translational	4.36	Y direction translational	-0.03	-1%	0.99
2	4.30	X direction translational	4.27	X direction translational	-0.03	-1%	0.99
3	1.58	X direction translational	1.58	X direction translational	0.00	0%	1.00
4	1.53	Y direction translational	1.52	Y direction translational	-0.01	0%	1.00
5	1.36	Torsion	1.38	Torsion	0.02	1%	1.01
6	1.05	Y direction translational	1.05	Y direction translational	0.00	0%	1.00
7	1.05	X direction translational	1.05	X direction translational	0.00	0%	1.00
8	0.72	Torsion	0.76	Torsion	0.04	5%	1.05
9	0.72	Y direction translational	0.76	Y direction translational	0.04	5%	1.05
10	0.69	X direction translational	0.74	X direction translational	0.05	8%	1.08

11	0.54	Y direction translational	0.55	Y direction translational	0.01	2%	1.02
12	0.53	X direction translational	0.55	X direction translational	0.02	2%	1.02
13	0.50		0.51		0.01	2%	1.02
14	0.43		0.43		0.00	0%	1.00
15	0.38		0.39		0.01	1%	1.01
16	0.37		0.38		0.01	1%	1.01
17	0.37		0.37		0.00	1%	1.01
18	0.31		0.31		0.00	0%	1.00
19	0.30		0.30		0.00	0%	1.00
20	0.28		0.28		0.00	0%	1.00

Table 2 shows that the periods of model B are nearly the same with model A in the first 20 natural modes. The cycle deviation of model B and model A ranges from 0s to 0.05s; the cycles deviation ratio to model A ranges from 0% to 8%; and the cycles ratio of model B to model A is close to 1. The two models both have 5 of X-direction translational modes, 5 of Y-direction translational modes, and 2 torsional modes in 12 lower-order natural modes. The periods and modes showed that model B could reflect the structural response characteristics of model A.

4.2 The Verification by Response Spectrum Analysis

The tower's seismic fortification intensity is 7; classification of anti-earthquake design is Group I; the peak acceleration is 0.1g; the site category is Class II. According to 'technical specification for concrete structures of high-rise building', the maximum earthquake affecting coefficient, α_{max}, of frequent earthquakes is 0.08; the maximum earthquake affecting coefficient, α_{max}, of strong earthquakes is 0.5; the site period value T_g is 0.35s; and the damping is 0.05. The story displacement and the story acceleration of the structure are shown in Fig.4 when response spectrum analysis is carried out
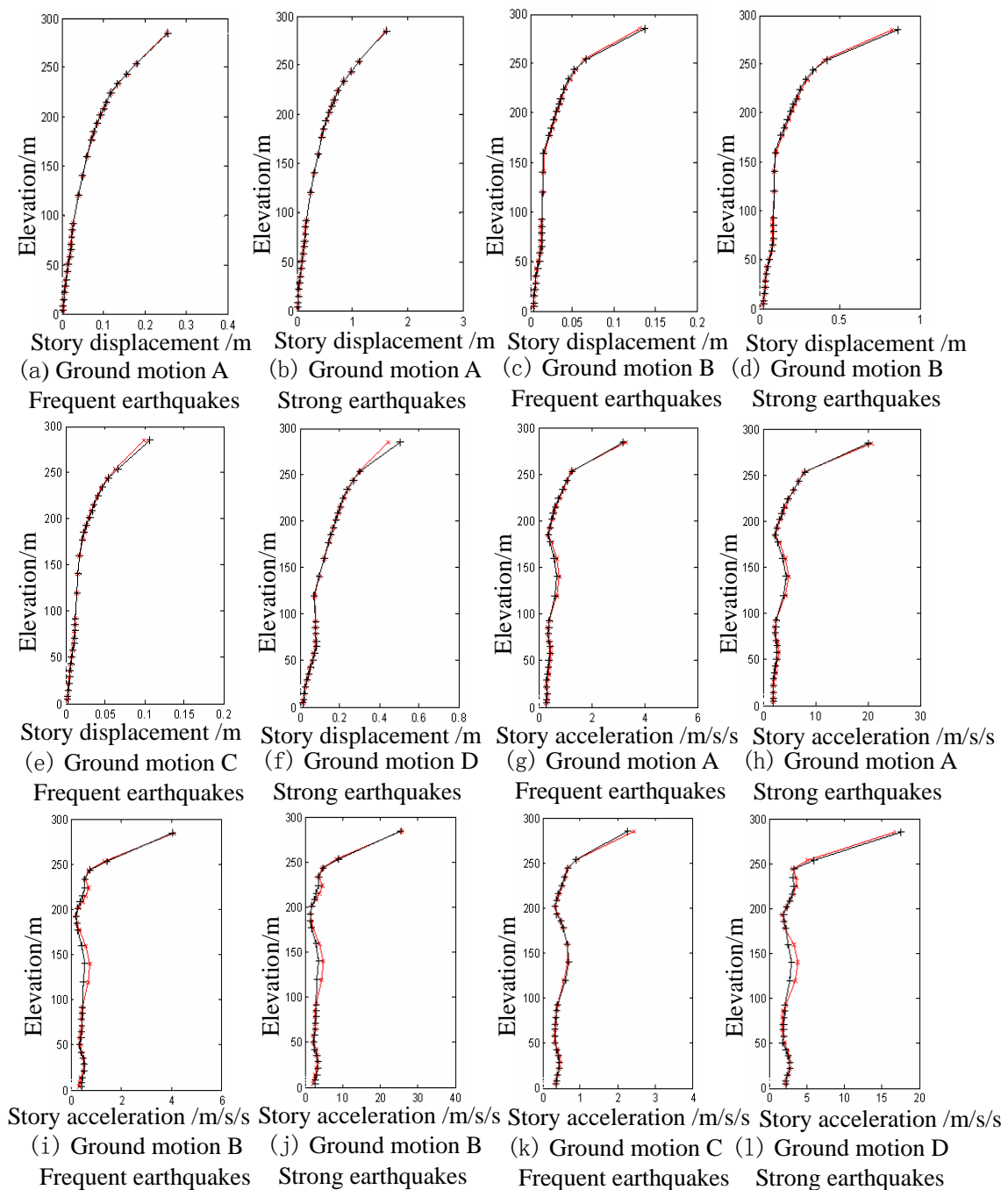

(a) Frequent earthquakes (b) Strong earthquakes (c) Frequent earthquakes (d) Strong earthquakes
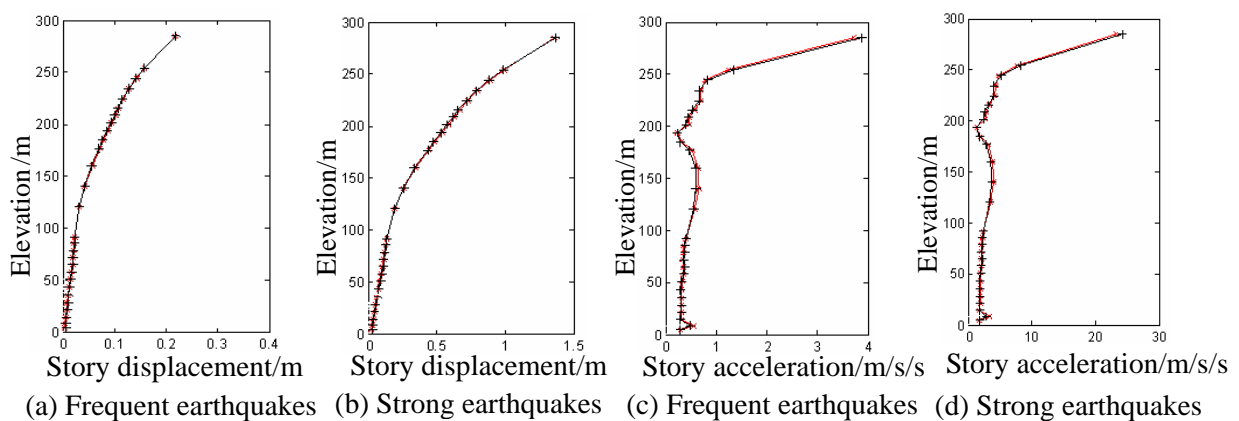
note：red（x）delegates model A; black（+）delegates model B

Fig.4 story displacement and story acceleration when response spectrum analysis is carried out

From fig.4, the story displacement and story acceleration of model B agrees well with model A's. The maximum deviation of the story displacement is 18.9%; while the minimum deviation of the story displacement is 0.2%. The maximum deviation of the story acceleration is 14.1%; the minimal deviation of the story displacement is 1.4%. The results of the response spectrum analysis prove the feasibility of the substitute method.

4.3 The Verification by Time History Analysis

Based on the rule 3.3.5 of 'technical specification for concrete structures of high-rise building', two actual seismic records and one artificial ground motion used for analyse structure are selected to according to building site categories and design characteristic. Duration of earthquake should be between 3 and 4 times of the building structure natural period, and more than 12s; the time step could be either 0.01s or 0.02s. What's more, in consider of the severest design ground motion, ground motion records used for analyse structure are the N69W component of 1979-El Centro-Array #10-Imperial Valley CA (ground motion A), the N21E component of 1952-Taft-Kern County (ground motion B), artificial ground motion under frequent earthquake actions (ground motion C), artificial ground motion under strong earthquake actions (ground motion D). The results of time history analysis are shown in Fig.5.

Story displacement /m
(a) Ground motion A
Frequent earthquakes

Story displacement /m
(b) Ground motion A
Strong earthquakes

Story displacement /m
(c) Ground motion B
Frequent earthquakes

Story displacement /m
(d) Ground motion B
Strong earthquakes

Story displacement /m
(e) Ground motion C
Frequent earthquakes

Story displacement /m
(f) Ground motion D
Strong earthquakes

Story acceleration /m/s/s
(g) Ground motion A
Frequent earthquakes

Story acceleration /m/s/s
(h) Ground motion A
Strong earthquakes

Story acceleration /m/s/s
(i) Ground motion B
Frequent earthquakes

Story acceleration /m/s/s
(j) Ground motion B
Strong earthquakes

Story acceleration /m/s/s
(k) Ground motion C
Frequent earthquakes

Story acceleration /m/s/s
(l) Ground motion D
Strong earthquakes

Note：red（x）delegates model A; black（+）delegates model B
Fig.5 Story displacement and story acceleration when time history analysis is carried out

Fig.5 is the story displacement and story acceleration of the offshore tower structure under seismic ground motion. The story displacement and the story acceleration of model B agrees well with model A's; and the error is small. The results of time history analysis prove that the upper structure seismic response performance of model B could be used to conduct the design of prototype structure. The feasibility of the substitute method is affirmed once again by time history analysis.

5. CONCLUSION

The substitute method provides an important way to simplify the SSI in the seismic simulation shaking table test. This method requires that every order mode period should be approximately equal, which can be realized by use of ETABS software. The seismic responses of the two models are consistent in the mode analysis, response spectral analysis and time history analysis. Especially, during the model analysis the mode shapes of the model A and model B distribute in the same way and they have very close periods; and the error ranges in 0% to 8%. During response spectral analysis, model B and model A almost has the same story displacement and story accelerations. The minimum deviation of the story displacement is 0.2%, while the maximum is 18.9%. Apparently, the maximum deviation is pretty large but it exists only in the base floors. From 28.6 m to 285 m the deviations in the story drifts are no more than 5%. For story accelerations, the minimum deviation and the maximum deviation are 1.4% and 14.1% respectively. During the time history analysis, the story drift distributions and story acceleration distributions of model A and model B are almost the same with slight deviation. All of these analyses show the credibility and applicability of the substitute method. However, this method is available only if the upper structural seismic response could be considered equivalently. It does not take into account of the forces acting on the foundation, so it still needs to be improved. But the substitute method gives a novel idea in the shaking table test and it is beneficial for researchers to carry out the SSI earthquake simulation shaking table test within limited conditions.

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