A Centrifugal model study for Bearing Capacity of the Spudcan Foundation in Soft Clay Soils with Increased Undrained Shear Strength

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ABSTRACT
Spudcan foundations are used for operating smooth penetration at seabed and getting sufficient bearing capacity in Jack-up system just like Jack-up rig and Jack-up type Wind Turbine Installation Vessel. Conventionally, bearing capacity of spudcan foundation is calculated by using SNAME guideline and DNV standard which are accepted as an industry standard. In this paper, 100 g-level centrifuge model test for bearing capacity of spudcan foundation in clay layer is operated. Bearing capacity of spudcan foundation and cone resistance for soil properties is measured during experiment, so obtained penetration curve and soil properties with depth are presented in this paper. 3D Finite Element Method of Coupled Eulerian-Lagrangian method in ABAQUS/Explicit is carried out to be compared with experiment results. Uniform and increased strength clay are used in FE analysis and guideline calculation and compared in this study. Consequently, bearing capacity considering increased undrained shear strength shows more realistic results than uniform case.

INTRODUCTION
Jack-up system installed in a Jack-up rig and a Jack-up type Wind Turbine Installation Vessel (WTIV) perform elevating legs and raising its hull. In the Jack-up system, spudcan foundation supports an overall platform contacting with subsoil beneath the each leg. Since the subsoil of Korea southwest sea is weak soil consisting of almost soft clay, the study about bearing capacity of spudcan foundation is necessary for operation of Jack-up type platform. There are three methods in the spudcan bearing capacity study; semi-theoretical and semi-empirical methods recommended in the guidelines (e.g. SNAME, DNV standard), Finite Element (FE) method with soil engineering model, and model test method [1]. Centrifuge model test, which is kind of model test, is used to simulate the spudcan penetration behavior. Centrifugal field is replaced with high gravity field in soil engineering study, so effective pressure at soil particle is precisely re-created by scaled model and high gravitational acceleration and soil behavior involved in the penetration of spudcan foundation is simulated. The bearing capacity study of spudcan foundation is performed by using three above-mentioned methods about single clay soil which is similar to subsoil of Korea southwest sea. In a previous study, increased undrained shear strength with depth was considered to calculate bearing capacity. Hossain et el. perform the clay strength gradient with depth study [2, 3], and also research with Randolph about spudcan penetration response on both uniform clay and nonhomogeneous clay [4]. Bearing capacity calculation method using soil profile at the Gulf of Mexico which has increased undrained shear strength is conducted by Menzies et el. [5]. Undrained shear strength is one of the most important parameter in clay behavior, thus it is necessary to research about the correlation between increased undrained shear strength and bearing capacity of that soil for realistic prediction. The present study presents calculation of bearing capacity in increased undrained shear strength soil condition according to each three method, and compare the result with each other. Soil in centrifuge model test is modeled with similar water content and preconsolidation pressure to that of Korea southwest sea, and measured soil properties are used in modeling the soil in FE analysis and guidelines.

SPUDCAN AND SOIL CONDITION
Spudcan foundation is inverted conical structure for penetrating and supporting leg and hull in the soil. Spudcan used in the experiment has large contact surface due to weak soil at southwest sea of South Korea.

Octagonal shape is adopted for the largest area on a limited width considering structural issue. Fig. 1 shows the details of used spudcan.

Through boring investigation, most sites of southwest sea have weak subsoil just like clay or thin sand surface layer. Fig. 2 depicts the soil profile of investigated eight boreholes in target field. Single clay is selected as soil condition used in experiment because this is the weakest soil condition among investigated boreholes in the range of design depth 30m.

RESEARCH METHOD

Centrifuge model test is the experiment which makes the model spin at a high speed and dominated by centrifugal field. Spinning model is simulated just like having a high gravity acceleration, so embodying a real stress state of field with soil depth. For preserving similarity, the equation of similarity ratio is as follows.

$$\sigma = \rho(Ng)\frac{H}{N} = \rho g H \quad (1)$$

According to the equation (1), stress state is proportionate to gravitational acceleration and depth. Therefore, 1/N of similarity ratio with N of gravitational acceleration makes the same stress as that in the field. In this case, force has $1/N^2$ of similarity ratio. Considering the dimension of spudcan and the centrifuge instrument capacity, 100 of N value and corresponding 1/100 scaled model is used in experiment. Fig. 3 is the centrifuge instrument of K-water used in experiment. Experiment model consists of soil container, actuator for spudcan penetration, actuator for Cone Penetration tester (CPT), and several sensors: 1/100 scaled model spudcan, loadcell for bearing capacity, CPT for soil properties, Pore Pressure Transducer (PPT), Total Pressure Transducer (TPT). Fig. 4 is the simplified diagram of experiment equipment.

Experiment procedure is as follows. First, combine kaolin and water to make slurry of 150% moisture content. Next is performing consolidation with 100kPa of field investigated preconsolidation pressure. Using frame, install spudcan penetration model and equipment on the soil container. After perform consolidation with 100g-level condition for applying field overburden stress, penetrate spudcan in 0.37mm/s uniformly and measure reaction force.

FE analysis is performed by using the Coupled Eulerian-Lagrangian (CEL) method of Abaqus/Explicit. In lagrangian description, the movement of the continuum is specified as a function of its initial coordinates and time, so lagrangian description is able to define interface between two parts precisely but occur element distortion at large deformation. On the other hand, instantaneous position and time are important factor in eulerian description. This description has no element distortion but tends to describe interface imprecisely. The CEL method uses lagrangian description for structure and eulerian description for subsoil to capture the strength of these two description [6]. Fig. 5 is FE analysis model of spudcan penetration. This model is made of real scale equivalent with an experiment soil, thus 55m of soil depth, 70m and 45m of boundary height and radius is used corresponding to each value of 0.55m, 0.70m and 0.45m which are the created soil depth and the soil container dimension.

Mohr-Coulomb model, which is the mathematical model describing soil failure, is used for clay soil. 637 kg/m^3 of submerged unit weight measured in experiment is used in the FE model, as well as v=0.49 for the poisson's ratio to ensure the undrained state for the clay during the penetration. Table shows the undrained shear strength and elastic modulus applied in the model.

Three layered clays are modeled in "Increased S_u" case to apply increased undrained shear strength by depth. Each layer has the average value measured by CPT in its range and single layered clay in "Uniform S_u" has that of overall depth.

RESULTS

Soil properties in centrifuge experiment was measured in cone resistance (q_c) value using the modified CPT sensor in which cone had pushed into the ground at a steady rate and the resistance to penetration was measured. Undrained shear strength (S_u) and Elastic modulus (E_s) were calculated from q_c value by using conversion equation as below.

$$S_u = \frac{q_c - \sigma_v}{N_{kt}}, \; E_s = \alpha_E (q_c - \sigma_v) \quad (2)$$

N_{kt} : bearing capacity coefficient, 10~18

$$\alpha_E = 0.015\left[10^{(0.55 I_c + 1.68)}\right]$$

I_c : Soil behavior index, 3.6 for silty clay-clay

Fig. 6 is the plot about q_c measured by experiment, S_u and E_s calculated by q_c. Measured q_c increase with the soil depth, thus graph of S_u and E_s have also shown increasing value with the soil depth.

Loadcell above the spudcan measured the reaction force which could be substituted for the bearing capacity of spudcan. When real scaled bearing capacity of spudcan is needed, measured force is multiplied by 100^2 because the ratio of force similarity is N^2. Reaction force measured in centrifuge experiment is in Fig. 7. Vertical reaction force of rigid spudcan structure can be also replaced to bearing capacity of spudcan in FE analysis. Real scaled spudcan being used in FE model, $1/100^2$ of factor is used to attain the results in model scale. The results from two groups of FE analyses conducted in this paper shown at Fig. 7: "Uniform S_u" and "Increased S_u". The results by the SNAME guideline methods for the two cases (as illustrated above) are compared with the FE predictions, as well as the experiment data in Fig. 7 [7].

In comparison between experiment and FE analysis results, result of experiment is larger than that of FE analysis. Slopes of both two cases in FE analysis are changed earlier than experiment result and convergence of bearing capacity is shown at about 200mm depth unlike the experiment. Profile of experiment shows that the bearing capacity increases rapidly in early phase of the profile and slope is gradually decreased with the depth and become uniformly. On the other hand, SNAME results have almost uniform slope in each layer.

DISCUSSION

This present study presents about effect of increased undrained shear strength with soil depth on bearing capacity using three analysis method; centrifuge experiment, FE anlysis and SNAME guideline calculation. Increased S_u phenomenon have been already treated in SNAME guideline and a number of study applied this phenomenon when they calculate bearing capacity at the various site. Clay strength gradient with depth study was performed by Hossain et al. in centrifuge tests and numerical analysis and concluded that entirely different soil flow pattern appeared between two cases of different strength gradient. Compared with the cases using uniform clay, the case with non-uniform clay showed larger normalized bearing pressure and lower penetration where the back-flow failure occurred [2, 3].

Soil investigated at real field and used in centrifuge experiment were "Increased S_u" case, thus the measured bearing capacity in experiment don't converge under the depth of 150mm and is increased linearly. Early phase of graph, bearing capacity is increased rapidly due to shear failure. Both two profiles of FE analysis has high slope at shallow depth similar with experiment, but bearing capacity isn't increased and converge at sufficient load when the undrained shear strength is uniform. "Increased S_u" case of FE analysis is also linearly increased after high slope range like experiment result, since soil failure point goes deeper than that of "Uniform S_u". The most different thing between experiment and "Increased S_u" case of FE analysis is the range of slope rapidly increased, in other words, slope of FE profile is decreased earlier than that of experiment. So after that the disparity of bearing capacity between two profiles is almost consistent. The reason why two profiles are separate could be soil model used in FE analysis; Mohr-Coulomb model. Because shear failure of soil is according to Mohr-Coulomb failure criterion in this model, the fast failure point of FE profile could be caused by the inappropriate failure criterion of soil model. The results by the SNAME guideline show the similar results with experiment, but there are no change of slope due to shear failure. Almost linearly increased profiles in each layer cannot show the real behavior of soil during penetration, and these results can be accepted to approximate value for design.

In this paper, it is thought that more realistic behavior and corresponding bearing capacity can be predicted with consideration of increased undrained shear strength in clay layer. However, there are some limitations about this result. First, illustrated above, there is difference about soil failure point in FE analysis expected because of soil engineering model. Second, this study model the "Increased S_u" case to three layered clay which have more and more large undrained shear strength. It is expected that natural and realistic result is obtained if increased value is modeled continuously.

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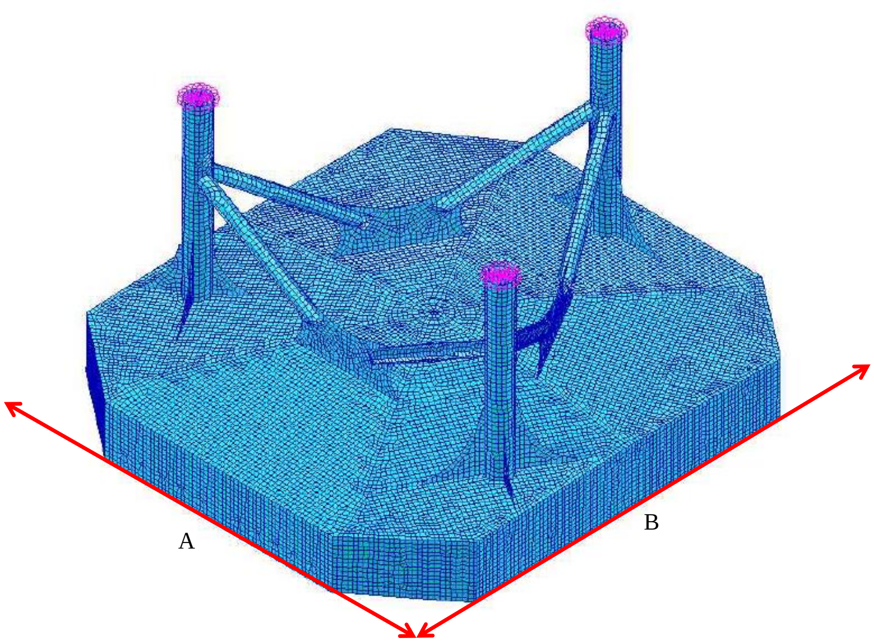
FIGURES



A	$10.32m$
B	$11.60m$
Effective Area	$112.8m^2$

Figure 1 Detailed dimension of used spudcan

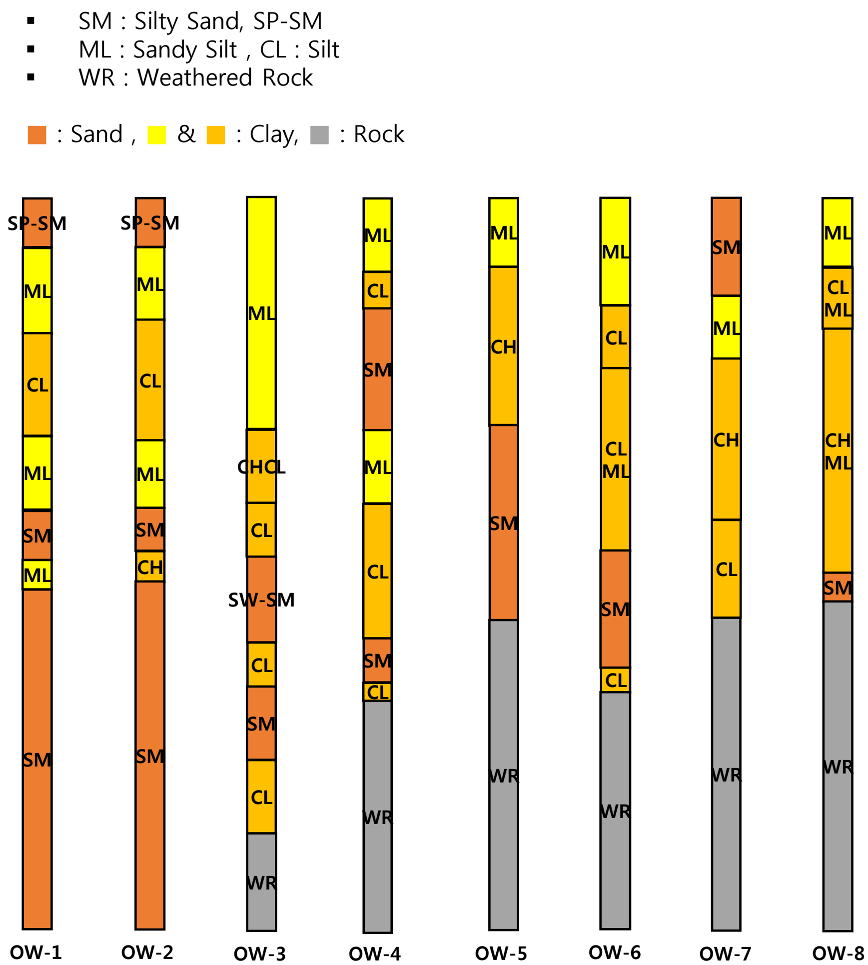


Figure 2 Soil profile of investigated boreholes in Korean southwest sea

Figure 3 Used centrifuge instrument in K-water

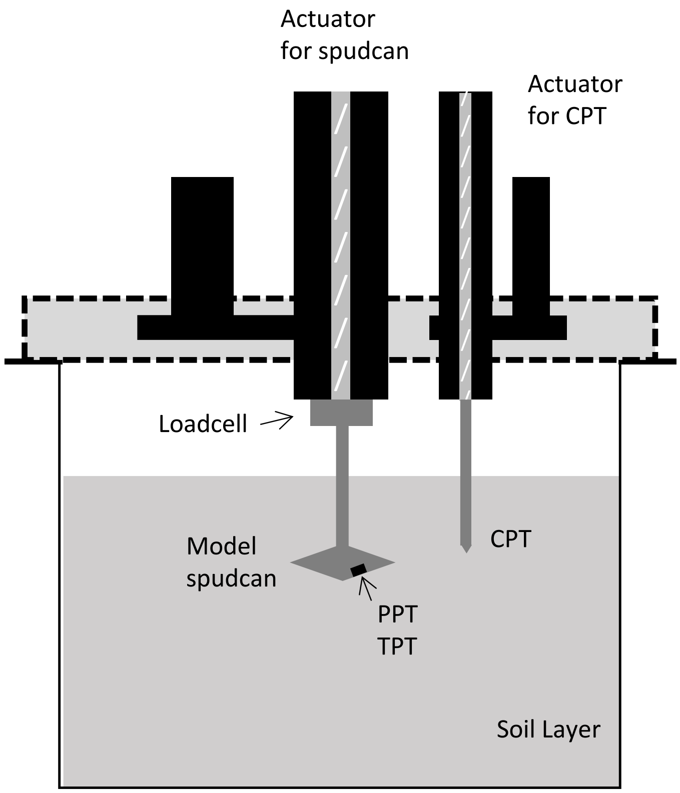


Figure 4 Simplified diagram of spudcan penetration model

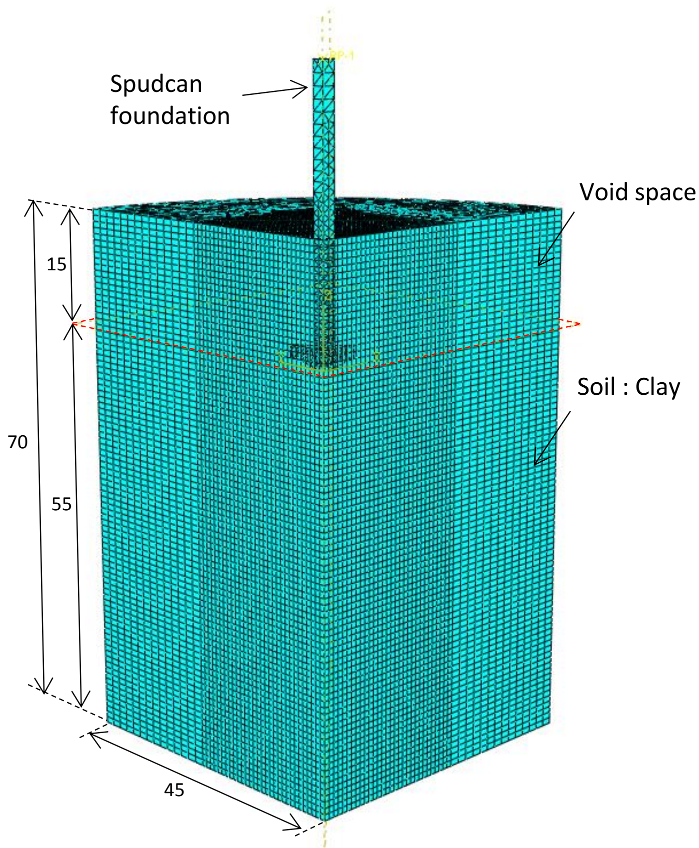


Figure 5 Equivalent FE model with centrifuge experiment

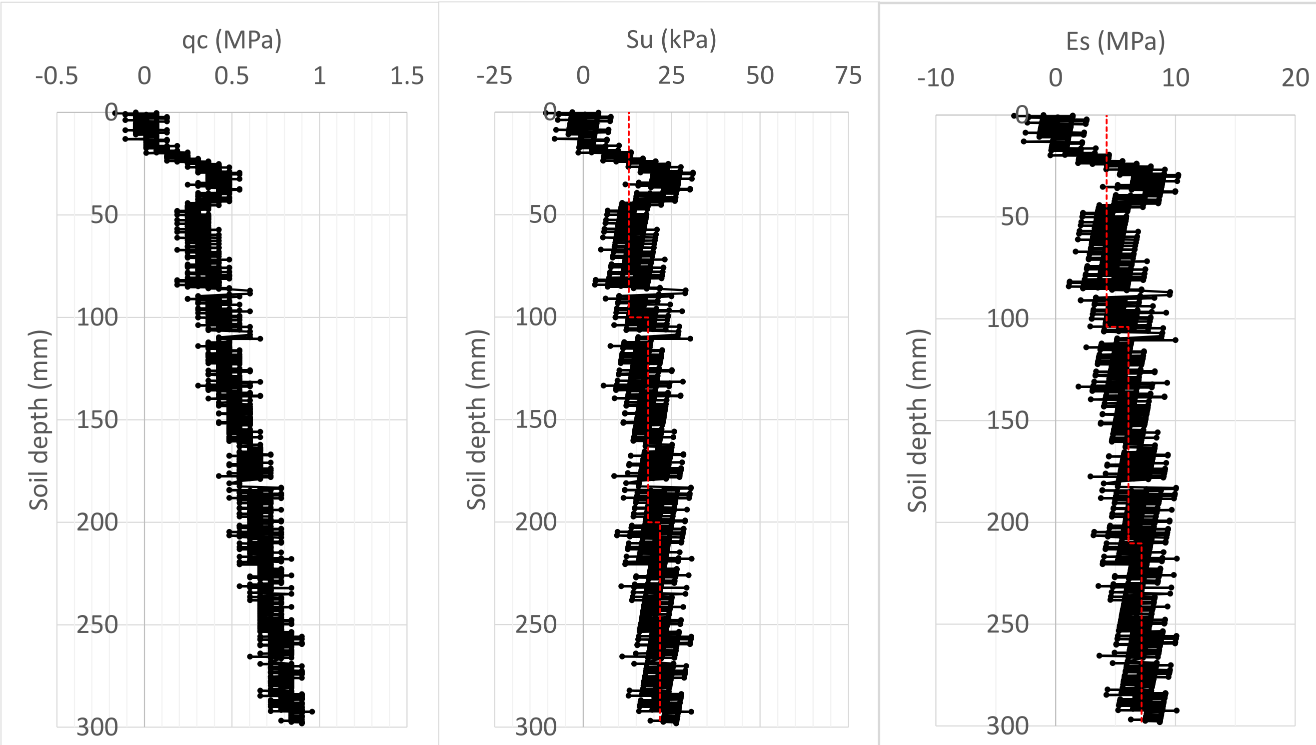


Figure 6 Results of cone resistance, undrained shear strength and elastic modulus measured in cone penetration test

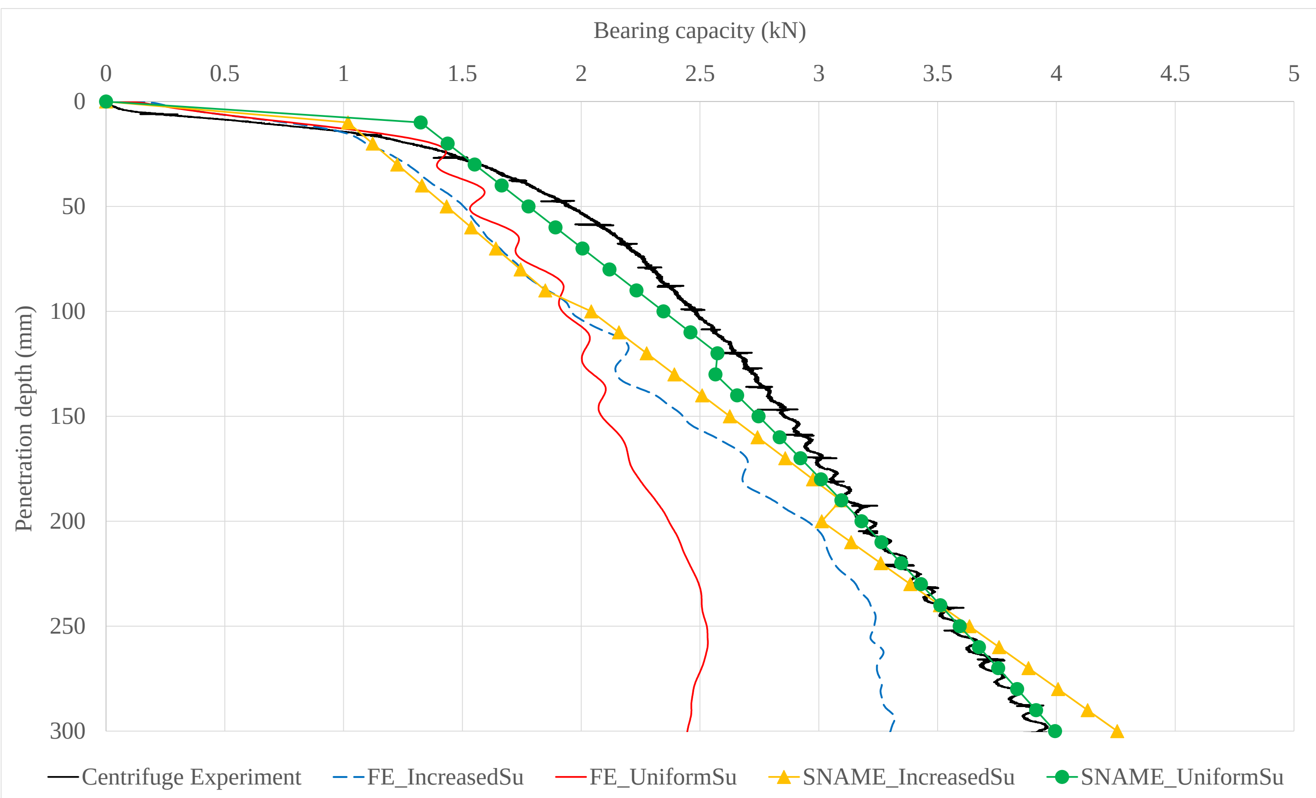


Figure 7 Compared results of centrifuge experiment, FE analysis and SNAME guideline in model scale

TABLES

TABLE 1: Soil properties used in FE analysis and SNAME guideline

Classification	**Depth**	**Undrained shear strength, kPa**	**Elastic modulus, MPa**
Uniform S_u	All (avr value)	17.659	5.830
Increased S_u	0 ~ 100 mm	12.888	4.255
	100 mm ~ 200 mm	18.400	6.074
	200 mm ~ 550 mm	21.693	7.161