CENTRIFUGAL MODELING OF ENLARGED BASE FOUNDATION SUBJECTED TO PULL-OUT FORCE

SUKH B. GURUNGⁱ⁾, YOICHIROU NAKAZIMAⁱⁱ⁾, SAIICHI SAKAJOⁱⁱⁱ⁾ and OSAMU KUSAKABE^{iv)}

ABSTRACT

This paper presents the centrifuge modeling of a prototype pull-out test conducted on enlarged base foundation using undisturbed block samples so that prototype values could be possible to extrapolate from model results. Undisturbed block samples were directly procured in specially designed centrifuge model containers to avoid sample disturbance. Samples were also reconstituted in laboratory to compare the behavior of undisturbed and reconstituted models. The undisturbed models showed higher pull-out resistance than that of reconstituted models and suggested the preservation of cohesion and in-situ soil fabric in the undisturbed models. When the results of undisturbed model were compared with the prototype results, a successful prediction regarding pull-out resistance was observed. However, the centrifuge models over predicted displacements of the prototype test. The deviation may arise from the scale and particle size effect due to the lack of similarity in shear band thickness as the peak values of pull-out resistance occur at different displacements. Together with the previously published data, it may be inferred that there might exist a correction factor for displacement in order to match the centrifuge data with the field test data.

Key words: centrifuge modeling, correction factor, displacement, particle size, prototype test, pull-out test, reconstituted model, scale factor, undisturbed model (IGC: E14/E4)

INTRODUCTION

The variation of soil properties with increasing depth of soil stratum, and its non-linear stress-strain behavior, the fragile structures and many other complex behaviors have made the determination of soil parameters a difficult task. In absence of correct parameters, predictions from numerical models might differ from the actual soil behavior. Usual practice is therefore, to perform a field test and confirm the in-situ soil behavior before under taking actual design work. However, any prototype test is costly, labor intensive, time consuming and yet may require many tests if the concerned project area is large. For example, along the alignment of highways, railways, tunnels or transmission line towers where soil properties vary from location to location. Under such conditions physical modeling may be an alternative approach to study soil behavior.

In many occasions, geotechnical centrifuges are used in physically modeling field related problems and have been reported to model the soil behavior successfully in both clayey and sandy soils (Lyndon and Schofield, 1970;

Basset and Horner, 1979; Fujii et al., 1988; Kusakabe et al., 1992). Therefore, in this research a recently developed Mini-Drum centrifuge which has a facility to sample undisturbed block samples directly into the container was used in modeling a prototype pull-out test of an enlarged base foundation.

SOME CONSIDERATIONS FOR MODELING

For modeling the prototype test following factors were considered. Model in the centrifuge is a scale down model and therefore, it is extremely difficult to match all the prototype conditions into a small piece of specimen. However by using undisturbed block samples in centrifuge, the centrifuge models represent more closely to actual in-situ soil fabric than could be modeled in other modeling technique. Figure 1 shows a schematic diagram of enlarged base foundation embedded in the natural ground and corresponding model of the same foundation in a centrifuge container. The total vertical geostatic stress in natural ground is shown to vary linearly with the depth and the prototype stress may be calculated by Eq.

ⁱ⁾ Research Associate, Dept. of Civil Engrg., Hiroshima University, 4-1, Kagamiyama 1-chome, Higashi-Hiroshima 739-8527.

ⁱⁱ⁾ Manager, Kansai Electric Co., Ltd., 3-3-22, Nakanoshima, Kita-ku, Osaka 530-0005.

ⁱⁱⁱ⁾ Manager, Kiso-Jiban Consultants Co., Ltd., 11-5, 1-chome, Kudan-kita, Chiyoda-ku, Tokyo 102-0073.

^{iv)} Professor, Dept. of Civil Engineering, Tokyo Institute of Technology, Ookayama, Meguro-ku, Tokyo 152-8552.

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Fig. 1. An enlarged base foundation in natural ground and in centrifuge model test

(1).

$$\sigma_p = \rho g D = \gamma D. \quad (1)$$

To simulate this stress condition, model in centrifuge is subjected to acceleration for producing similar stress conditions at homologous points. Stress in centrifuge model, along the model vertical direction can be calculated by Eq. (2).

$$\sigma_m = \int_0^{H_m} \rho \omega^2 (R_t + h) dh = \rho \omega^2 H_m (R_t + 0.5 H_m). \quad (2)$$

Equation (2) suggests that soil model in centrifuge experiences zero stress at free soil surface and increasing stress at the model vertical direction which is similar to the prototype stress. To achieve the same stress condition at homologous points, let us equate Eq. (1) and Eq. (2) and consider the scale factor $(N) = D/H_m$, then the required angular velocity (ω) of centrifuge can be calculated from Eq. (3).

$$Ng = \omega^2 R_e \quad (3)$$

where, $R_e = R_t + 0.5 H_m$. In present study angular velocity was calculated for the prototype stress of 57 kPa acting at the base of the foundation. Using $R_e = 0.34$ m, and $\omega = 414$ rpm, maximum deviation of model stress from prototype stress was found to be 3.2%. From scaling laws, model pull-out resistance (P_m) and displacement (d_m) can be related to prototype pull-out resistance (P_p) and displacement (d_p) values by the following relations.

$$\frac{P_m}{P_p} = \frac{1}{N^2} \quad (4)$$

$$\frac{d_m}{d_p} = \frac{1}{N} \quad (5)$$

where, N is scale factor. These relations have been used in relating centrifuge model values into prototype values.

Scale Effect

For calculating the angular velocity of centrifuge, a scale factor (N) was introduced in Eq. (3) which can produce scale effects while extrapolating model values. One of the ways to check the scale effect is by the principle called modeling of model (Malushitsky, 1981; Gempertline, 1988) in which various models scaled down by the factor N are subjected to the centrifugal acceleration field of Ng modeling the same prototype scale $((1/N) \times Ng)$, where, g is acceleration due to gravity. A similar approach was also taken to carry out modeling of model tests in this Mini-Drum centrifuge. Figures 2(a) and (b) show the modeling of model test results (Kusakabe et al., 1996) using Leighton Buzzard sand, grade (100/170). Model tests were carried out by pulling out the enlarged base footings under axisymmetric condition to observe the modeling potential of Mini-Drum centrifuge. Three model tests SBG-1, SBG-2 and SBG-3 were conducted at the scale factors of 65, 97.5 and 130 respectively so that all the models represent the same prototype. Dimensions of the model footings are presented in Fig. 2(a). The extrapolated test results show the variation in peak pull-out resistance (P_{max}) = 1.2%. Therefore, remaining very close to the lower modeling range, a scale factor of 65 was adopted in this study. At this scale factor, a model footing of $H_m = 50$ mm and $B_m = 37$ mm closely corresponds to prototype foundation of $D = 3.15$ m and $B = 2.33$ m respectively as shown in Fig. 1.

Particle Size Effect

The centrifugal model test using the same soil from prototype test site, deviates in the sense that similarity concerning the grain size is not fulfilled due to the fact that the prototype sand is used in the model. However, review of literature suggests that centrifuge modelers seem to adopt a technique by keeping certain number of particles in contact with the foundation base i.e. ascertaining $B_b/$

(a) Model values

Fig. 2. Modeling of models

D_{50} ratio greater than certain number to avoid particle size effect. For examples, Yamaguchi et al. (1977) studied the bearing capacity problems using Toyoura sand of $D_{50}=0.18$ mm, by varying the width of foundations ($B_b/D_{50}>110$) at different scale factors. They reported an insignificant influence of particle size on the bearing capacity problem. Gooding and Gillete (1991) conducted a series of slope stability test and concluded that particle size effect was not noticed when the slope height was 500 times D_{50} . Similarly, for circular footings, Ovesen (1979) adopted a technique to avoid particle size effects by keeping the ratio of footing diameter (B_b) to D_{50} greater than 15. In this study, Ovesen's approach was followed and the ratio of B_b/D_{50} was kept greater than 45 (Table 1). But increasing B_b can result in interference of shear plane propagation by the model container boundary. Therefore, a following measure was taken to avoid boundary effects.

Boundary Effect

The internal dimensions of the centrifuge model container are 165 mm width 165 mm breadth and 115 mm

Table 1. Model values of undisturbed and reconstituted models

Model test (1)	B_b (mm.) (2)	$\frac{B_b}{D_{50}}$ (3)	D_r (%) (4)	P_{max} (kN) (5)	d_{max} (mm.) (6)
SBun-1	36	46	84.2	0.432	2.5
SBun-2	39	50	84.5	0.529	1.4
SBun-3	39	50	86.3	0.566	1.8
SBdist-3	39	50	95.4	0.376	0.6
SBdist-4	43	55	89.4	0.438	1.0
SBdist-7	39	50	89.3	0.349	1.3

depth. Therefore, the clear spacing between internal face of the model container and edge of 37 mm base diameter of model footing (B_m)= $[(165-37)/2]=64$ mm giving the ratio of clear width (B_m) to model depth (H_m) i.e. $B_m/H_m=64/50>1$. This suggests that even if failure planes propagate with an angle of 45° to vertical, container boundaries would not interfere the failure plane. Meyerhof and Adams (1968) have reported that under the pull-out condition, the failure surface in the sand beds varies between $\phi/3$ to $2\phi/3$ with the vertical. This supports the fact that the side ends of model container will not significantly affect propagation of shear plane.

FIELD PULL-OUT TEST

A schematic diagram of the test site is given in Fig. 3. The sampling site was chosen near the actual in-situ test site to minimize the variation in soil parameters.

Site and Soil Properties

Geologically the soil group around the sampling area is categorized as Osaka group, which is a sedimentary deposit. In this study, the soil has been named as Seika sand after the name of sampling place. The soil is grayish brown in color and at some places contains some fraction of weathered granite and oxidized layers of sand. The grain-size distribution curve is shown in Fig. 4. From the drained triaxial compression tests, the effective friction angle (ϕ') and effective cohesion were found out to be 40.5° and 15 kPa respectively.

Fig. 3. A schematic diagram of test site

Fig. 4. Grain size distribution of Seika sand

Prototype Pull-out Test

The development of an excavation process has made it possible to cast enlarged base foundations at shallow depth without disturbing the soil mass above the enlarged base foundation; soil mass above the line of excavation (Fig. 1). Adoption of enlarged base foundation thus results in utilizing the in-situ strength of soil mass and saving in construction cost of the foundation. This may lead to preference of short enlarged base foundation over conventionally driven long piles especially for transmission tower foundations passing through hilly terrain. One of such enlarged base concrete foundations was therefore, tested under pull-out load in service territory of Kansai Electric Company for field assessment. The general view of the field loading system is shown in Fig. 5. Three hydraulic jacks, each of 1962 kN capacities was used to apply the pull-out load on the reinforced concrete footing. The vertical displacement of the footing was measured at top of the foundation by a linearly variable differential transducer (LVDT) attached to the reference beam. The test was a load control test, applying the loads in steps, in each step only 49 kN load was applied. At the end of each loading, the applied load was held constant for 15 min to stabilize jack pressure. Total pull-out load was applied in two cycles as shown in Fig. 6. The first one being to check the integrity of system where the load was applied step by step up to 412 kN and then rebound back

Fig. 5. General view of field loading system

to zero. The second cycle of load was applied in the same way till the end of the test.

At the end of the test, cracks developed on the ground surface as well as on the excavated cross-section were traced by coloring the cracks with blue color spray. Pictures of these cracks, both on plan view and excavated cross-sections were taken by camera and video for reproducing the sketch of the cracks. The sketch is not exactly identical to the actual cracks because the picture

Fig. 6. Two cycles of field pull-out test

Fig. 7. Failure surface (field test)

scales are distorted due to the lens aberration of camera and video. Figure 7(a) shows the sketch of failure surface on plan view. In the radial direction a series of tension cracks were developed whereas in circumferential direction shear lines were observed. Figure 7(b) shows the cross-sectional view of the failure soil mass. Many shear planes or discontinuity lines were observed above the enlarged base of the foundation. The discontinuity lines were spreading away from the shaft of the foundation toward the ground surface. Outer boundary of the shear plane separating the stationary part of the soil mass and discontinuity lines can be drawn as a curve resembling to a sector of log-spiral from point A to B and a straight line from point B to C as shown in Fig. 7(b).

CENTRIFUGE TEST

Mini-Drum and Test System

The Mini-Drum centrifuge consists of an 800 mm diameter drum that can be driven to produce the maximum acceleration of 445 g. The drum is driven by a 4.4 kW brushless servo drives with a user interface control panel. Mini-Drum has been described in detail elsewhere (Kusakabe et al., 1996). A PC was used to record the data continuously during the flight. Data were multiplexed by on board electronics, housed in the drum and routed through the slip rings to the PC for storing. In this study, data were sampled at every 0.6 sec to monitor the pull-out behavior continuously. An actuator was fitted in the drum to pull-out the model footing caste in the model. A strain gauged load cell, designed to measure a maximum pull-out load of 1.92 kN, was connected to the actuator in one end and model footing through threaded rod to other end (Fig. 8). Pulling of model footing exerted the force on the load cell, which was recorded as pull-out resistance of the model. During pull-out, vertical displacement of the model footing was measured by a

Fig. 8. A test set-up showing the cross section of centrifuge model

RS-type solartron DC-15, linearly variable differential transformer (LVDT). The load cell and LVDT were calibrated in the centrifuge against dead weights and micrometer readings respectively, with the centrifuge driving motor on, to produce similar electrical environment as in model tests to incorporate electrical noises. Raw data of model tests were subjected to a standard low pass Bessel filter to smooth the high frequency electrical noises. Models were pulled at a constant rate of 5.5 mm/min under the axisymmetric condition.

MODEL SPECIMENS

Undisturbed Models

The undisturbed block samples were collected from Sakanaka Gun, Kyoto prefecture, Japan. According to the boring log, the soil was uniform up to 5 m depth. Therefore, it is believed that the block samples were truly representative of the in-situ sand. About 5 m away from the actual field test site, a trench was excavated to take the block samples. Three block samples, each of 165 mm width 165 mm breadth and 170 mm depth were procured from a depth of 0.6 m. The block samples were directly sampled in the specially designed centrifuge model container for Mini-Drum centrifuge to avoid sample disturbance (Gurung, 1996). A block sample taken in the centrifuge model container is shown in Fig. 9. The sample was produced by keeping 30 mm projection from both ends of the container. This was done to preserve in-situ soil structure while waxing and tightening the top and bottom plates of the steel enclosure. Therefore, for this reason steel enclosure was made 60 mm deeper than model container allowing 30 mm projection from each end. Three specimens of undisturbed model hereafter named SBun-1, SBun-2, and SBun-3 were procured in three different model containers.

Reconstituted Models

Beside undisturbed block samples, from the same pit specimens were also collected for preparing reconstituted models to study the behavior of remolded models. Five percent water by weight, was added to dry Seika sand and mixed thoroughly to prepare reconstituted specimens. The top and bottom portion of the specimen were

Fig. 9. Block sample in the model container

kept projecting out from the centrifuge model container in the same way as undisturbed model to adopt the same method of scarifying during model preparation. Coarse grains and fine grains were placed randomly in an attempt to match the soil matrix in the field. The models were prepared by compacting the sand in 10 layers to maintain the uniformity in models. In each layer a known weight of sand was compacted to pre-determine volume for controlling total unit weight of specimen. Three reconstituted specimens hereafter called SBdist-3, SBdist-4 and SBdist-7 were prepared with total unit weights at 17.5 kN/m^3 .

FREEZING AND DRILLING OF SPECIMEN

Both undisturbed and reconstituted models enclosed in the steel enclosure were kept at -40°C to freeze the specimens. Due to the freezing, the compressive strength and shear strength of the specimen may have increased by more than twice (Jumikis, 1966). So it is believed that drilling of specimen for casting model footing did not cause any disturbance on the soil fabric, as cracks were not visible on the specimen. After freezing, the specimen was hard like conglomerate. Two drills of 25 mm and 37 mm diameter, with a general precise taper shank twist were used for drilling the specimens. The 37 mm diameter drill was modified to drill the same enlarged base angle (β) of model footing. The 25 mm diameter hole and 37 mm diameter hole represents a shaft diameter of 1.62 m and a base diameter of 2.4 m at 65 g. Immediately after drilling, all models were transferred and installed in the Mini-Drum centrifuge to preserve the in-tact structure while the specimen was still in frozen state.

CASTING OF MODEL FOOTING

In the drilled hole a threaded rod of 6 mm diameter with three nuts was used for reinforcing the model footing. The threaded rod was connected to the strain gauged load cell as shown in Fig. 8. The model footing was casted from a hemi-hydrate gypsum slurry having a gypsum/water ratio of 0.7 by weight as this ratio was found to be appropriate for pouring. Figure 10 shows one of the model footings casted from gypsum slurry. The model was allowed to thaw in a room temperature for 15 hours. After 15 hours the model footing was found to be strong enough for pull-out test. The model was then carefully scarified layer by layer to required depth to preserve the in-situ soil structure.

RESULTS AND DISCUSSIONS

Figure 11 shows the comparison of load-displacement curves of undisturbed models and reconstituted models, plotted in terms of prototype values. The undisturbed models show higher pull-out resistance (marked as region of undisturbed models) than that of the reconstituted models (marked as region of reconstituted models), in spite of lower relative densities (Table 1) and conforms

the preservation of in-situ soil behavior in undisturbed models. After attaining peak value, the pull-out resistance of the undisturbed model decreases sharply. This behavior reflects the deterioration of intrinsic cohesion present in the in-situ soil. At large displacements, both undisturbed and reconstituted curves are overlapping each other and show the attainment of residual strength. This behavior further demonstrates that the structures of undisturbed soil models are broken and cohesion has been fully deteriorated.

After confirming the preservation of in-situ behavior of undisturbed samples, the results of undisturbed models were compared with prototype test results (Fig.

Fig. 10. Model footing made from gypsum slurry and threaded rod

Fig. 11. Pull-out resistance vs. displacement curves of undisturbed and reconstituted models

Fig. 12. Prediction of prototype values by undisturbed models

12). The undisturbed models showed smooth and sharper peaks than the prototype one. This is believed to be due to the difference in loading system. Note that the centrifuge model tests were of displacement control test whereas prototype test was of load control test. However for the sake of comparison, the highest values of the field pull-out test was taken as prototype peak value as the load-displacement curve start curving. It is noteworthy that P_{max} of the field test is lying below the P_{max} of SBun-2 and SBun-3 but above the P_{max} of SBun-1 and indicates that the centrifuge models can reasonably predict P_{max} of field test. The average P_{max} of three undisturbed models (2150 kN) was compared with prototype peak value (2158 kN) and found to be well predicted.

Tatsuoka et al. (1991) while conducting study on progressive failure and particle size effect of footing on sand, observed that shear band is dominated after attaining the peak value of load-settlement curves. In Fig. 12 initial slopes of the load-displacement curves of prototype test and undisturbed models are similar where the effect of shear band is not dominant. However, the peak value of prototype test has occurred at smaller displacements than those of the undisturbed models, which implies the lack of similarity in shear band thickness. Due to this dissimilarity, a deviation in displacement takes place when model values are extrapolated to prototype values. To investigate further on the reason of deviation, test data were reviewed on direct comparison between centrifuge model and field test reported by other researchers.

Fujii et al. (1988) carried out a series of centrifugal model tests in an attempt to directly compare with a large scale field loading test. For modeling they used a beam centrifuge of 3.05 m radius and model tests were carried out at $N=20$. The natural sand procured from field loading site was Shirasu sand having $D_{50}=0.24$ mm. Similarly, to simulate a large-scale in-situ loading test on granular material, Kusakabe et al. (1993) carried out a series of centrifuge model tests using the Scoria sand, having

$D_{50}=1.57$ mm procured from test site. The model tests were conducted at $N=13.3$ on a beam centrifuge of 1.18 m. Note that Figs. 13 and 14 reproduced from Fujii et al. and Kusakabe et al. respectively, show good prediction of prototype values by centrifuge tests up to the peak values, it should be mentioned that both tests were loading or push-in tests. However, for proper matching of prototype values a correction factor was necessary to apply to the extrapolated values of the centrifuge model test. By trial and error, it was found to be approximately 3 for normalized displacements of the collected results. Similarly, in present study also although it is a pull-out test, irrespective of loading conditions when a correction factor of 3 was applied to normalized displacement of model values, a good agreement between prototype and model displacement was able to obtain (Fig. 15). Note that the corrected model curves follow the field data up to the residual state. These plots certainly suggest that some correction factor is needed when extrapolating the cen-

Fig. 13. Comparison of centrifuge simulation with field test (Modified from Fujii et al., 1988)

Fig. 14. Comparison of centrifuge simulation with field test (Modified from Kusakabe et al., 1993)

Fig. 15. Comparison of prototype test result with modified results of undisturbed models

trifuge model displacements to prototype values both under push-in or pull-out conditions. This shows that for granular material, Eq. (5), may be modified as

$$\frac{d_m}{d_p} = \frac{\alpha}{N} \quad (6)$$

where, α is the correction factor of displacement. From the present study $\alpha \approx 3$. However, if the correction is due to the lack of similarity in shear band thickness as a result of using the same sand in model and prototype, the factor may be mainly a function of particle size (D_{50}) and scale factor (N). The integrated discrepancy between the field data and the centrifuge data may be stemmed from various reasons, such as disturbances during sampling and model preparation, mobilization of cohesion, particle size and scale factor. However, at present contribution of each factors can not be separated and further research is required. An initial attempt of numerical simulation using FEM analysis in carrying out the effect of shear band thickness in predicting prototype values has been attempted by one of the authors (Sakajo and Sakai, 1997).

It is also worth mentioning both Fujii et al. and Kusakabe et al. used undisturbed block samples of 60 cm $\times$ 40 cm $\times$ 40 cm and 40 cm $\times$ 20 cm $\times$ 18 cm size respectively in beam centrifuge. Therefore, their samples are 21 times and 3 times larger than the present block samples and the radius of centrifuges are nearly 8 times and 3 times longer than the present one. This suggests that by using smaller undisturbed block samples, comparatively smaller centrifuge is also useful in modeling the practical problem and therefore can be an educational tool in teaching laboratories because of simplicity in operating the machine and handling the models.

CONCLUSIONS

Based on the present study the following conclusions have been made:

(1) A comparison between load-displacement curves of undisturbed and reconstituted models shows that the undisturbed samples give higher pull-out resistance than reconstituted samples despite the higher relative densities reflecting the significant of cohesion and soil fabric of undisturbed models.

(2) The peak pull-out resistance of the prototype test was reasonably predicted by the extrapolated peak values of undisturbed models and indicates that the problem of reproducing prototype stress level is possible to solve in small centrifuge model.

(3) The centrifuge models over-predict the prototype displacement, which was also found to be true in the case of other researchers and indicates the necessity of applying a correction factor on the extrapolated model displacements of granular materials irrespective of push-in or pull-out loading conditions. In present study, introduction of correction factor on the model values made the corrected curve to follow the field test data up to the residual state.

(4) Despite the small effective radius and use of small block samples, the Mini-Drum centrifuge models showed similar results as that of bigger beam centrifuge and indicated the possibility of using small diameter centrifuge in understanding the physical phenomena of geotechnical problems in teaching laboratories.

NOTATIONS

The following symbols are used in this paper:

- N = Scale factor
- g = Acceleration due to gravity
- B_b = Base diameter of footing
- B_m = Clear spacing between footing edge to internal face of the container
- H_m = Model depth
- R_e = Effective radius from the center of centrifuge
- R_t = Radius at top of the model
- D_{50} = Average grain size
- C_u = Coefficient of uniformity
- C_c = Coefficient of curvature
- G_s = Specific gravity
- ϕ = Angle of shearing resistance (degree)
- $P_{\max}$ = Peak pull-out resistance
- $d_{\max}$ = Displacement at peak pull-out resistance
- c = Cohesion
- γ = Unit weight of soil
- D_r = Relative density of soil
- D = Depth of foundation
- ω = Angular velocity.

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