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Distribution of Residual Load and True Shaft Resistance for a Driven Instrumented Test Pile

Reply to Discussion

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We are very pleased that the discussers have provided us with a reason to re-visit our paper. The back-calculated secant modulus relation of the Myeongji pile combined with the strain of 1,200 με gives a calculated axial load of 5,700 kN for when the pile broke at a load of about 6,000+ kN. The 5,700 kN load corresponds to a stress of 32 MPa (over the 1,810 cm^2 cross section; the paper omitted to include the information that the wall of the Myeongji test pile was 30 mm thicker than that of the standard pile), well below the 80 MPa concrete cube strength and well below the axial strength of a standard pile. The primary reason for the break was the structural weakening of the concrete caused by the multitude of strain-gage cables in the pile wall, particularly where they were elbowed out of the pile shortly below the pile head. Figure 1 shows a photograph of the pile head after the collapse.

The secant modulus relation evaluated from the test on the grouted Shinho pile and the maximum strain (1,300 με) measured for the Shinho head-down test (cross section 2,830 cm^2) matches the axial load of about 9,000 kN when the pile plunged. The applied stress was then 33 MPa. There was no indication of any impending failure of the pile. It should be noted that the purpose of grouting the central void in the Shinho test pile was not to strengthen the pile, but to house the gages so they would not interfere with the pile wall.

The discussers correctly state that "*the key design aspects for this site are actually the maximum load in the pile and the pile structural strength*". We agree, and the main objective and the emphasis of the paper was to determine the maximum load in the piles and its actual location in the pile—the neutral plane. As to the structural strength, we prefer to correlate the limiting axial stress or load in the pile to a strain value, emphasizing strain compatibility between the concrete and the steel rebars, instead of correlating it to the compressive strength of the concrete. We did not elaborate on these points in the paper, as the objective of the paper was to present the results of the case study, not to detail the structural design of the piles at the site.

In addressing general principles as a background to the PHC pile, we suggested general and conservative limit values of strain (1,500 με) and combined E-modulus (30 GPa) be used for determining the nominal limit stress (structural axial strength) of the PHC pile. The discussers mention that the limit strain could be as high as 2,000 με. Using the actual relations for the pile modulus of the test piles and applying the mentioned strain limits gives maximum load values of about 6,800 to about 8,700 kN for the Myeongji test pile, and about 11,000 to about 13,500 kN for the Shinho test pile. The design needs to apply a suitable factor of safety to these limits, of course.

Fig. 1 The pile head immediately after the break

Where a design analysis for particular soil conditions and pile lengths indicates that the maximum load in the piles at the neutral plane (dead load plus drag load) will be larger than the safe limit, the piles need to be strengthen. At the subject project, because the testing programme had established the prevailing conditions at the site, in areas of the site where the maximum load in the piles were determined to be approaching and exceeding the required strength of the standard PHC pile, piles were ordered with a larger wall thickness that provided the required extra axial strength. Strengthening the piles by grouting was not used, as its effect was considered uncertain. Of course, in case of extreme loading, an additional increase of strength could still be obtained by grouting the void in the PHC pile—as well as supplementing the grout with steel reinforcement if yet more strength would be required.

The 8 MPa prestress for the standard 600 mm PHC pile with 24 rebars corresponds to an axial load of about 1,100 kN over the cross section (area 1,375 cm^2) and a precompression strain in the pile of about 300 $\mu\varepsilon$. For the pretensioned rebars (total area = 16 cm^2), the 1,100 kN axial load corresponds to about 3,500 $\mu\varepsilon$ strain and about 700 MPa tension, i.e., about 50 % of yield (a bit lower than used for prestressed concrete piles in North American practice, which uses wire strands, not rebars). If axial loads impose a strain close to the limiting value of 1,500 to 2,000 $\mu\varepsilon$, about half of the net prestress will be "unloaded". To include the remaining about 100 to 200 $\mu\varepsilon$ compression strain due to prestressing in the design considerations is theoretically correct; however, the analysis would then also have to include the reinforcing effect of the rebars. The formula quoted by the discussers is one commonly applied to prestressed piles in North America, where the wire strands are considered to contribute little to the axial strength in compression. Their contribution is therefore omitted from the consideration, as opposed to the contribution of the deformed rebars in the PHC pile.

When assessing the maximum load in a pile, the full history of strain in the pile needs to be considered and include strain changes due to the residual load, the sustained load applied to the pile from the structure, and the drag load (accumulated negative skin friction). Strain changes in the pile from the driving and during soil set-up were recorded also for the Myeongji test pile (to save space, the data were left out of the paper). The strains after end of driving were similar to those reported for the Shinho pile: an increase of compression strain of up to 400 $\mu\varepsilon$ at depth, while near the pile head, due to swelling, the pre-test strains were about 100 $\mu\varepsilon$ in tension. For the construction piles, some of these strains will be offset by the sustained load applied to the pile. The long-term settlement of the soils surrounding the pile will then result in drag load and a neutral plane will develop. The paper presented the long-term strain and the maximum load in the Shinho test pile at the neutral plane as caused by the several contributing factors. This is the mechanism that the design for the conditions of maximum load must take into account.

We have difficulty understanding the discussers' comments about "allowable load". The term "allowable load" commonly refers to the maximum working load applied to a pile head. For the subject project, the working load ranges from 2,000 through 2,300 kN, which is many times smaller than the maximum load applied to the test pile in the static loading tests and the capacity of the piles proven in the Shinho test. The pile length is governed by the need for the piles to be long enough for the neutral plane to be located in non-settling soil. The key design aspect of this paper is the analysis of the location of the neutral plane and the maximum load at the neutral plane, that is, the sustained portion of the working load (the dead load) plus the drag load. Figures 19 and 20 in the paper indicate distribution of load for the long-term condition at the Shinho and Myeongji sites, respectively. The two figures show load distributions and the respective locations of the neutral plane where the maximum loads occur. When assessing whether or not the maximum load at the neutral plane can be safely tolerated by the pile, it is necessary to assess it in terms of strain.

Perhaps our difficulty is because the discussers appear to use the net prestress value of 8 MPa over the cross section of the standard 90-mm wall pile as the pile rebar net pretension. The rebar net pretension, however, is actually about 700 MPa.