Large-scale Piled Raft with Grid-Form Deep Mixing Walls on Soft Ground

Comportement en vraie grandeur d'une fondation mixte radier-pieux établie dans un sol meuble amélioré par quadrillage de mélange profond de sol

Yamashita K., Wakai S., Hamada J.
Research & Development Institute, Takenaka Corporation, Chiba, Japan

ABSTRACT: This paper offers a case history of a large-scale piled raft supporting a twelve-story building founded on liquefiable sand underlain by soft cohesive soil in Tokyo. The building, 55.7 m in height above the ground surface and measuring 120 m by 100 m in plan, is a steel-framed structure with a base isolation system of laminated rubber bearings. An assessment of a potential of liquefaction during earthquakes indicated that the loose clayey sand between depths of 5 and 15 m had a potential of liquefaction during earthquakes with the peak horizontal ground acceleration of 3.0 m/s^2. Therefore, a piled raft combined with grid-form deep cement mixing walls was employed to cope with the liquefiable sand and also to reduce settlements of the soft cohesive soil below the sand. To confirm the validity of the foundation design, field measurements were carried out on the foundation settlements, the axial loads of the piles, the contact pressures between raft and soil and the pore-water pressure beneath the raft from the beginning of construction to 11 months after the end of construction.

RÉSUMÉ : Cet article présente une étude de cas en vraie grandeur d'une fondation mixte radier-pieux d'un bâtiment à douze niveaux construit à Tokyo. Cette fondation est établie dans une couche de sable liquéfiable reposant sur une couche de sol cohérent et meuble. Le bâtiment, qui fait 120 m par 100 m dans le plan et 55.7 m en hauteur au-dessus du sol, a une structure métallique en portiques. Il est isolé à sa base par un système d'appareils d'appui en élastomère fretté. Le potentiel de liquéfaction estimé du sable argileux entre 5 et 15 m de profondeur serait atteint sous une acceleration horizontale maximum de 3.0 m/s^2. Pour pallier à ce phénomène et reduire le tassement de la couche sous-jacente de sol cohérent et meuble, une fondation mixte radier-pieux a été adoptée en combinaison avec l'amélioration, en forme de quadrillage, de la couche de sable par mélange profond. L'article discute le comportement de cette fondation sur la base d'une série de mesures sur site, qui se sont poursuivies depuis le début jusqu' à onze mois après la fin de la construction du bâtiment. Le dimensionnement de cette fondation est estimé convenable considérant les mesures de tassement, des forces axiales sur pieux, des contraintes sur le sol et de la pression de l'eau interstitielle sous le radier.

KEYWORDS: piled raft foundation, deep cement mixing wall, soft ground, field measurements, settlement, load sharing

1 INTRODUCTION

In recent years there has been an increasing recognition that the use of piles to reduce raft settlements can lead to considerable economy without compromising the safety and performance of the foundation (Poulos, 2001). Detailed investigations of many high-rise buildings founded on piled rafts in Germany have been carried out (Katzenbach et al. 2000). Piled raft foundations have been used for many buildings in Japan and the settlement and the load sharing between raft and piles have been carefully investigated for the selected buildings (Yamashita et al. 2011a; Yamashita et al. 2011b). It has become necessary to develop more reliable seismic design methods for piled rafts, particularly in highly seismic areas such as Japan.

This paper offers a case history of a large-scale piled raft supporting a twelve-story building founded on liquefiable sand underlain by soft cohesive soil in Tokyo. To cope with the liquefiable sand and also to reduce settlements of the soft cohesive soil below the loose sand, piled raft foundation combined with grid-form deep cement mixing walls was employed. To confirm the validity of the foundation design, field measurements were carried out on the foundation settlements, the axial loads of the piles, the contact pressures between the raft and soil and the pore-water pressure beneath the raft from the beginning of construction to 11 months after the end of construction. During the construction period, the 2011 off the Pacific coast of Tohoku Earthquake struck the site of the building. The effects of the earthquake on the settlement and the load sharing between the raft and the piles are also discussed.

2 BUILDING AND SOIL CONDITIONS

The twelve-story office building is located in Tokyo, 0.3 km southeast from the twelve-story residential building (Yamashita et al., 2011b). Figure 1 shows a schematic view of the building and the foundation with a soil profile. The building, 55.7 m in height above the ground surface and measuring 120 m by 100 m in plan, is a steel-framed structure with a base isolation system of laminated rubber bearings. The foundation levels were between depths of 3.6 and 7.2 m.

The subsoil consists of an alluvial stratum to a depth of 44 m below the ground surface, underlain by a diluvial very dense sand. The ground water table appears approximately 3 m below the ground surface. The soil profile down to a depth of 15 m is made of fill which consists of loose clayey sand, sandy clay and rubble. Between the depths of 15 to 44 m, there lie very soft to medium silty clay which is slightly overconsolidated with an OCR of 1.3 or higher. The shear wave velocities derived from a P-S logging were 150 m/s at the foundation levels and 290 m/s in the dense sand below the depth of 44 m.

3 FOUNDATION DESIGN

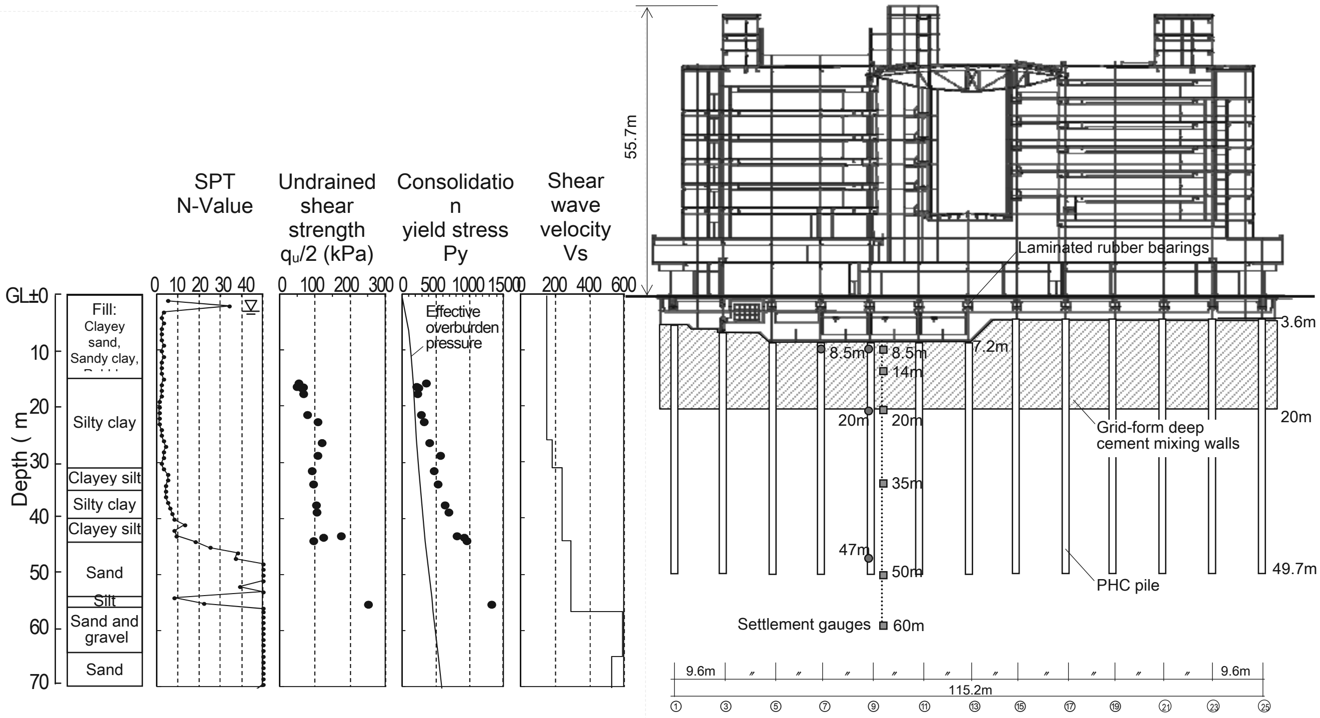


Figure 1. Schematic view of the building and foundation with soil profile

3.1 *Ground improvement*

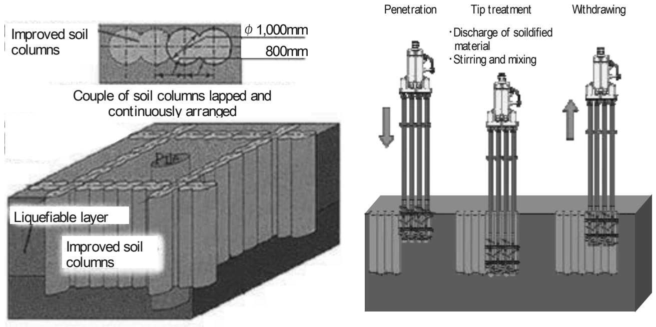
An assessment of a potential of liquefaction during earthquakes indicated that the loose clayey sand between the depths of 5 to 15 m had a potential of liquefaction during earthquakes with the peak horizontal ground acceleration of 3.0 m/s^2. The foundation level was between depths of 3.6 and 7.2 m, therefore, grid-form deep cement mixing walls were introduced to cope with the liquefiable clayey sand below the raft. Figure 2 shows the grid-form deep cement mixing walls constructed by TOFT method. The high-modulus soil-cement walls confine loose sand so as not to cause excessive shear deformation to the loose sand during earthquakes. The effectiveness of the TOFT method for the prevention of liquefaction was confirmed during the 1995 Hyogoken-Nambu earthquake (Tokimatsu et al., 1996).

3.2 *Design of piled raft*

The average contact pressure over the raft is 187 kPa. To improve bearing capacity of the raft, the grid-form deep cement mixing walls were extended to the depth of 20 m with the bottom being embedded in the silty clay with undrained shear strength of 100 kPa or higher. Furthermore, to reduce the settlement and the differential settlement to an acceptable level, 180 pre-tensioned spun high-strength concrete (PHC) piles of 0.6 to 1.2 m in diameter were used. The pile toes were embedded in the very dense sand below the depth of 44 m enough to ensure the toe resistance as well as the frictional resistance. The pile was constructed by inserting the precast piles into a pre-augered borehole filled with mixed-in-place soil cement. Figure 3 shows a layout of the piles and the grid-form deep cement mixing walls.

4 INSTRUMENTATION

The locations of the monitoring devices are shown in Figs. 3 and 4. Four piles, P1, P2, P3 and P4, were provided with a couple of LVDT-type strain gauges at depths of 8.5 m (near pile head), 20.0 m and 47.0 m (near pile toe) from the ground



(a) Grid-form deep cement mixing walls (b) Construction procedure

Figure 2. Grid-form deep cement mixing method

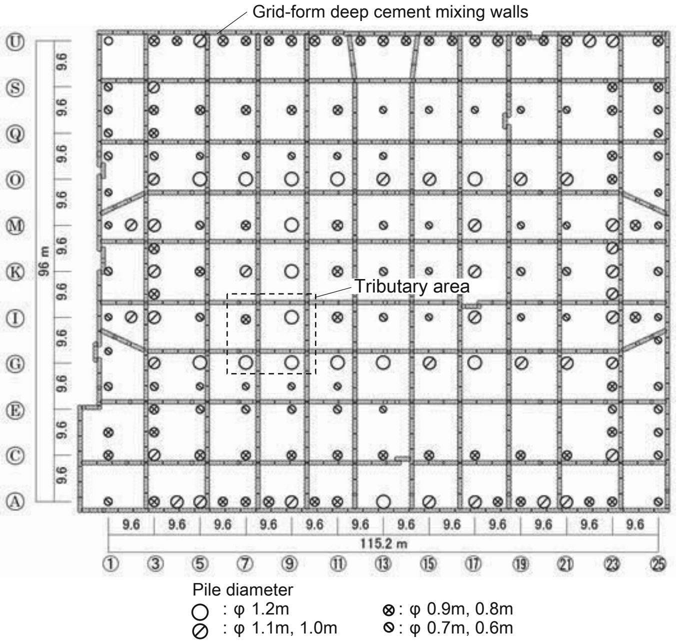


Figure 3. Layout of piles and grid-form deep cement mixing walls

surface. In the tributary area of the instrumented piles, six earth pressure cells and one piezometer were installed beneath the raft at the depth of 7.2 m. Earth pressure cells E1-E3 were installed on the intact soil and earth pressure cells D1-D3 were installed on the deep mixing walls. The vertical ground displacements below the raft were measured by differential settlement gauges. LVDT-type transducers were installed beneath the raft at depths of 8.5 m, 14.0 m, 20.0 m, 35.0 m and 50.0 m to measure the relative displacements to a reference point at a depth of 60.0 m. The settlements of the foundation were measured at the monitoring points on the raft by an optical level. The measurement of the vertical ground displacements was begun during the excavation for the foundation construction. The measurement of the axial loads of the piles, the contact pressures and the pore-water pressure beneath the raft was begun just before the casting of the 0.6-m thick foundation slab.

5 RESULTS OF MEASUREMENTS

5.1 *Foundation settlement*

Figure 5 shows the measured vertical ground displacements below the raft. The measured ground displacement at the depth of 8.5 m after the casting of the foundation slab, was approximately equal to the foundation settlement. The foundation settlement increased considerably just before the end of construction (November 15, 2011) due to the water pouring into the underground pits. Thereafter, the foundation settlement became stable and reached 21 mm 11 months after the end of construction (November 3, 2012). Figure 6 shows the settlement profile of the raft measured by the optical level just before the end of construction. The measured settlements were 12 to 24 mm and the maximum angular rotation of the raft was 1/1400 radian which satisfied the design requirements.

5.2 *Pile load and contact pressures*

Figure 7 shows the development of the measured axial loads of piles P1-P4. The axial loads also increased considerably just before the end of construction due to the water pouring. Thereafter, the pile-head loads reached 4.7-11.2 MN in November, 2012. Figure 8 shows the distribution of the measured axial loads on pile P1. Since the piles were surrounded by the deep mixing walls to a depth of 20.0 m, the skin friction of the pile shaft between the depths of 8.5 m and 20.0 m was quite small. The average skin friction between the depths of 20.0 m and 47.0 m was 76 kPa. The ratio of the pile-toe load to the pile-head load was 0.21 in November, 2012. Figure 9 shows the development of the measured contact pressures between the raft and the soil and the pore-water pressure beneath the raft. The measured contact pressures between the raft and the intact soil seemed to reach a state of equilibrium in early stage of the construction, while those between the raft and the deep mixing walls increased with construction loading in the same way as the axial loads of the piles. The measured contact pressures between the raft and the deep mixing walls were 137-180 kPa and those between the raft and the intact soil were 66-72 kPa just before the end of construction. The measured pore-water pressure was approximately 40 kPa..

5.3 *Load sharing between raft and piles*

Figure 10 shows the time-dependent load sharing among the piles, the soil, the deep mixing walls and the buoyancy in the tributary area of the instrumented piles shown in Fig. 4. The sum of the measured pile-head loads and the raft load in the tributary area varied from 61.3 to 62.0 MN after the end of construction, which was generally consistent with the design load of 64.0 MN. Figure 11 shows the ratios of the load carried

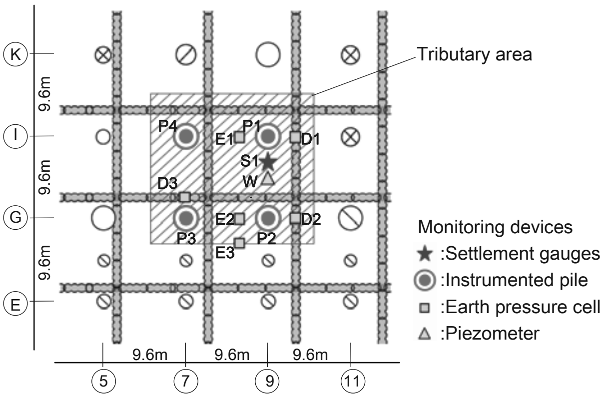


Figure 4. Locations of monitoring devices

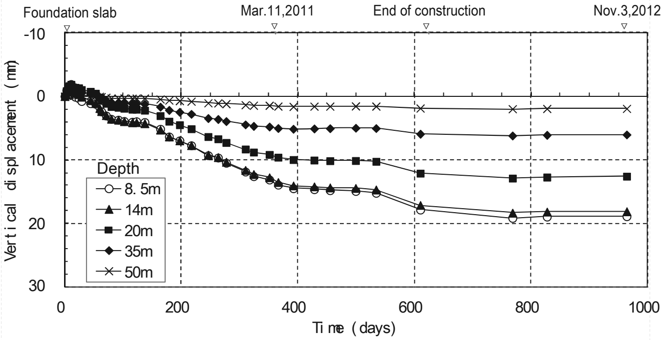


Figure 5. Measured vertical ground displacements below raft

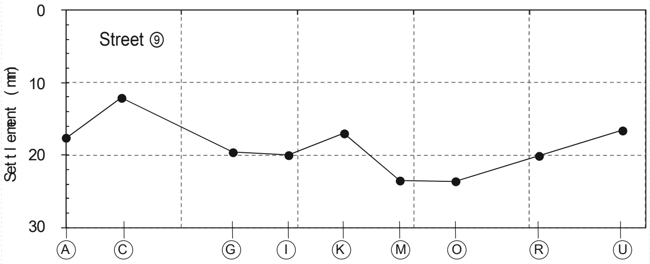
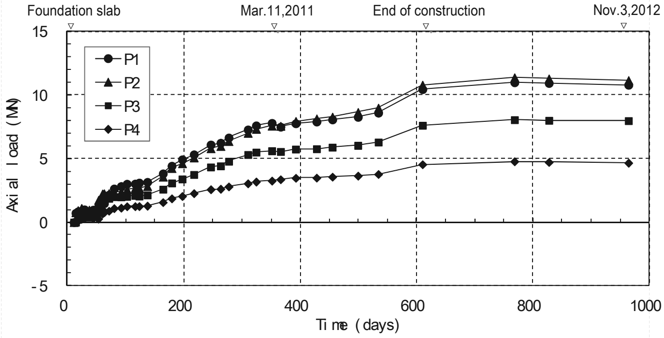
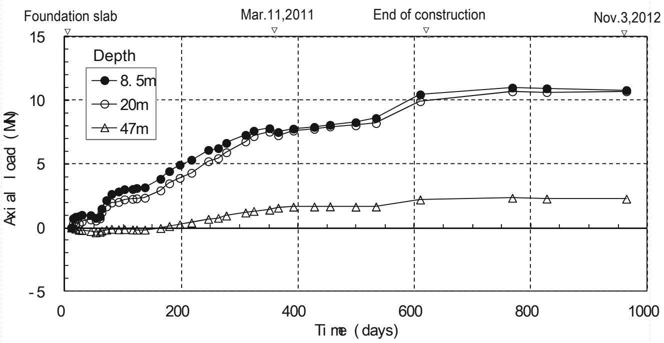


Figure 6. Measured settlement profile of raft



(a) Pile-head loads of piles P1 to P4



(b) Axial loads of pile P1

Figure 7. Measured axial loads of piles

by the piles to the effective load and that to the total load in the tributary area versus time. The ratio of the load carried by the piles to the effective load was estimated to be 0.70 just before the end of construction and increased only slightly to 0.71 in November, 2012. Meanwhile, the ratio of the effective load carried by the deep mixing walls to the effective load was 0.14 and the ratio of that carried by the intact soil to the effective load was 0.15 in November, 2012.

5.4 *Effects of earthquake on settlement and load sharing*

On March 11, 2011, nine months before the end of construction, the 2011 off the Pacific coast of Tohoku Earthquake struck the site of the building. At the site of the twelve-story residential building, the peak horizontal ground acceleration of 1.75 m/s^2 was observed (Yamashita et al. 2012). Although the contact pressures between the raft and the deep mixing walls were increased markedly as shown in Fig. 9(a), no significant changes in the foundation settlement or the load sharing between the raft and the piles were observed after the earthquake, as shown in Figs. 5 and 11.

6 CONCLUSIONS

Field measurements were carried out on the foundation settlement and the load sharing between the raft and the piles for the large-scale piled raft with the grid-form deep cement mixing walls on soft ground in Tokyo. The foundation settlement reached 21 mm and the ratio of the load carried by the piles to the effective load in the tributary area was estimated to be 0.71 11 months after the end of construction. During the construction period, the 2011 off the Pacific coast of Tohoku Earthquake struck the site of the building. Based on the measurement results, no significant changes in the foundation settlement or the load sharing were observed after the earthquake. Consequently, it is confirmed that a large-scale piled raft, combined with grid-form deep mixing walls, works effectively in grounds consisting of liquefiable sand and soft cohesive soil.

7 ACKNOWLEDGEMENTS

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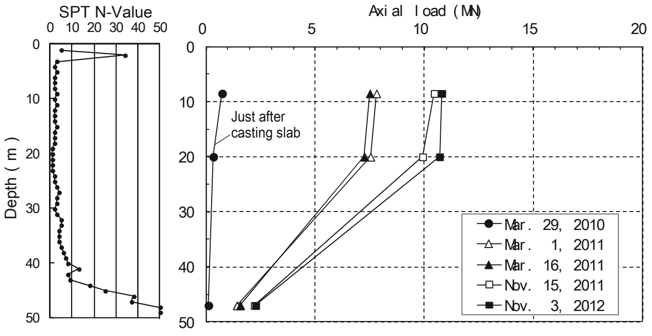
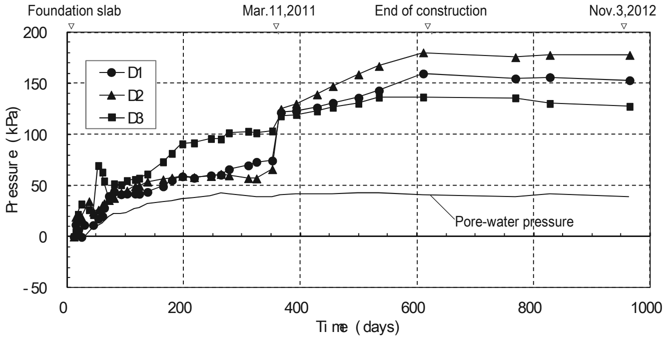
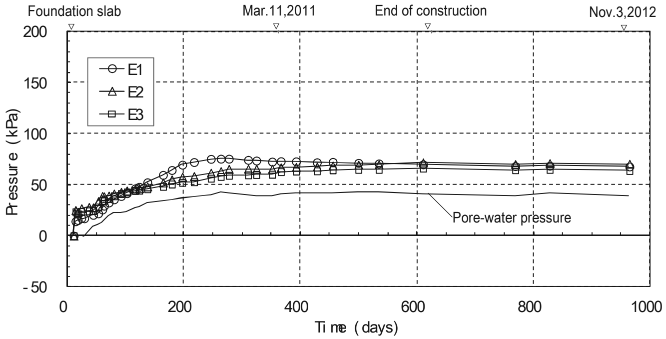


Figure 8. Axial load distribution on pile P1



(a) Contact pressures between raft and deep mixing walls



(b) Contact pressures between raft and soil

Figure 9. Measured contact pressures and pore-water pressure beneath raft

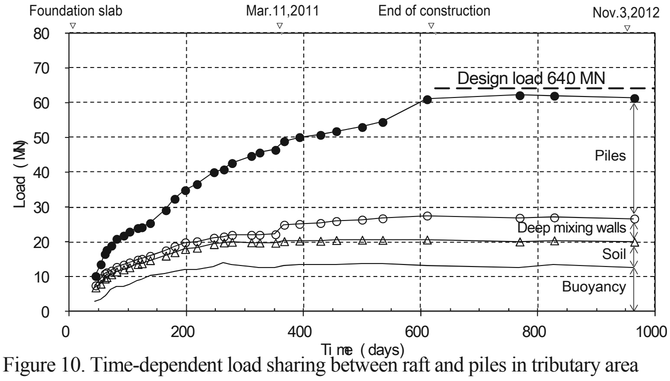


Figure 10. Time-dependent load sharing between raft and piles in tributary area

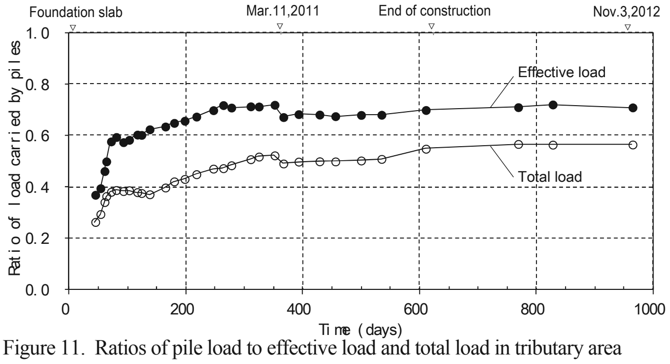


Figure 11. Ratios of pile load to effective load and total load in tributary area