Evaluation of Differential Settlement along Bridge Approach Structure on Soft Bangkok Clay

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Abstract. Excessive differential settlement along bridge approach is commonly found in the lower central region of Thailand. To overcome the differential settlement problem, engineers have developed different types of bridge approach structure and improved design procedures. Two types of bridge approach structure are currently used in Thailand, including the approach slab on ground and the approach slab on pile. This research conducts field investigation, subsoil exploration and laboratory testing, and long-term geotechnical instrumentation and monitoring program of two bridge approaches which were constructed in Bangkok and vicinity. After construction for 3 to 7 years, the study results show that the main cause of differential settlement along bridge approach is due to the foundation of bridge approach structure is rest on different soil layers having much different compressibility properties and thickness. The differential settlement problem is found at locations where the bridge approach foundation changes from end bearing pile to friction pile, and to shallow foundation. The long-term observations show that the differential settlement could cause a sudden change in the longitudinal slope and discomfort driver. Moreover, it could create large voids underneath the approach slab, failure of concrete slab, and damage of pavement and structure members along bridge approach. Back analysis results show that the settlement prediction using the Terzaghi consolidation theory and elastic theory with equivalent foundation approach for vertical stress distribution gives 0.44 to 1 times the value observed in the field.

Keywords. bridge approach structure, differential settlement, consolidation, soft clay

1. Introduction

The differential settlement along bridge approach is one of a common geotechnical engineering problem found in the lower Central region of Thailand. The main cause of the problem is that the highway embankment is on soft Bangkok Clay with high compressibility, whereas the bridge structure is rest on pile foundation transferring load to a stiff soil such as dense sand with low compressibility. In addition, material inspection, field compaction control, damage of a concrete approach slab, and deep groundwater pumping, high traffic load are also contributed to the settlement problem (Ardain, 1978; Briaud et al., 1997, 2003; Long et al., 2003; While, 2005).

Many researchers and engineers (Poophat, 1980; Rojanathara, 1985; Taesiri and Rojanathara, 1986; Buasruang, 2008; Saowiang, 2009; Vardhanabhuti et al., 2010; Holmberg, 1978; Seah and Wongsopit, 2000) found that the mechanism of large differential settlement magnitude at the bridge approach is due to the consolidation of soft Bangkok Clay. The problem could be minimized by many techniques such as relief pile foundation, lightweight embankment material, preloading technique with or without vertical drain, cement column and geotextile installation. Attention has been on the improvement in detail design, such as installing grout hole in the approach slab for mudjacking, using sleeper beam at approach slab connection for jacking, designing profile grade embankment higher than the bridge (Tadros and Benak, 1989; Briaud et al., 1997; Hoppe, 1999).

However, the long-term differential settlement problem still occurs; causing driver discomfort, speed reduction, traffic and safety problems. Differential settlement also causes damage to bridge approach structure such as barrier, approach slab, and crack and bumping of pavement.

2. Bridge Approach Structure

For engineering practice in Thailand, two types of bridge approach structure are commonly used, (1) approach slab on ground and (2) approach slab on pile, shown in Figures 1 and 2, respectively. The approach slab on ground

consists of reinforced concrete slab, having the width equal to the width of the bridge, 5 to 10 m long, and the thickness of 0.25 to 0.30 m. The slab is overlaid with 0.05 m asphaltic concrete. One end of the slab is rest on a beam transferring load from the bridge to pile foundation, and the other end is rest on compacted embankment. It is often used for small bridge across canal or conduit, in which the traffic and speed limit are low.
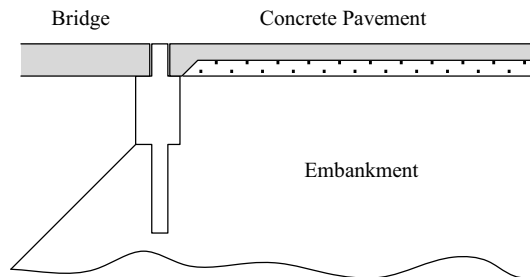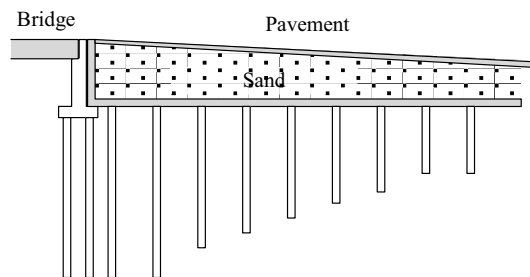

Figure 1. Approach slab on ground.

Figure 2. Approach slab on pile.

For approach slab on pile foundation or bridge approach support piling system (Reid and Buchanan, 1983) or commonly called in Thailand as "bearing unit system" (Leerakomsan, 1981; Rananand and Leerakomsan, 1982; Rungarunanotai, 2003), it consists of reinforced concrete slab of 0.2 to 0.3 m thick. The slab distributes the embankment load to the relief pile. The piles are generally installed in a square pattern with a spacing (center to center) of 2 m. The relief piles are divided into 3 zones including (1) low settlement zone, (2) transition zone, and (3) high settlement zone. For low settlement zone, the pile tip is in stiff soil layer with the length approximately equal to the pile of

bridge foundation. The design factor of safety is relatively high comparing to the transition and high settlement zone in order to minimize the differential settlement between bridge and bridge approach structure. For the pile in the transition zone, the pile length and its bearing capacity decrease. For the high settlement zone, the pile with a minimum length of 2 to 4 m is often used (Rojanathara, 1985; Rungarunanotai, 2003; Vardhanabhuti et al., 2010).

3. Settlement Observation along Bridge Approach Structure

Two bridge case studies were selected in Bangkok and vicinities (Figure 3), including (1) Klong Song bridge [Krungthep Krita – RomKlao (III) Road.], and (2) Klong Bang Ta Nai bridge [Highway No. 345 at Bang Bua Thong and Highway No. 7 intersection]. The bridges are 2 to 5 year olds during the study period, as summarized in Table 1 (Saowiang, 2009; Vardhanabhuti et al. 2010).

Table 1. Summary of two bridges used for the case study

Name	Approach structure	Finish construction (month/year)
Klong Song bridge	Approach slab on ground Slab - 10 m length - 0.3 m thickness	08/2004
Klong Bang Ta-Nai bridge	Approach slab on pile Slab - 45 m length - 0.23 m thickness Pile - 0.22-0.26 m (square section) - 4 - 22 m length	06/2007

Figure 3. Locations of case studies on soft Bangkok Clay.

Data from construction report and long-term geotechnical instrumentation were collected. The field observation data include (1) pore-water pressure and ground water table, (2) surface settlement and deep settlement, (3) horizontal and vertical movement of embankment. The longitudinal slope [different elevation between two points (ΔS)/ horizontal distance between two points (ΔL) x 100] was determined to check the location of differential settlement problem (Sunitsakul et al., 2008; Saowiang, 2009; Vardhanabhuti et al. 2010).

Examples of surface elevation measurement after construction are illustrated in Figures 4 and 5 for Klong Song bridge and Klong Bang Ta Nai bridge, respectively. Klong Song bridge used an approach slab on ground and the settlement was measured after 5 years and 2 months. The result shows that the settlement of bridge foundation is hardly observed, and the average settlement of highway embankment is 0.31 m. The differential settlement problem was noticeable at 2 locations, (1) connection between approach slab and bridge structure and (2) connection between approach slab and highway embankment. The change in slope ($\Delta S/\Delta L$ x 100) is high as 1.0% and 2.9%, respectively. These cause driver to reduce speed to avoid the impact between the bottom of bumper and the road surface.

In case of Klong Bang Ta Nai bridge, the average settlement of highway embankment after 2 years is 0.34 m. High differential settlement was found at 3 locations, (1) the connection between approach slab and bridge structure, (2) the connection between approach slab and highway embankment, and (3) the transition

zone where pile tips rest on soft and stiff soil layers as shown in Figure 5. At station 10+635 to 10+640 km., the piles have a length ranging from 16 m to 14 m and the piles tip are in very stiff sandy clay layer and soft silty to medium stiff clay layer, in respective order. The change in slope is in the range of 0.12 % to 0.29 %. Data from horizontal inclinometer, deep settlement plate, and a transverse pavement crack and barrier damage lead to a conclusion that the reinforced concrete approach slab was broken at about station 3+653 to 3+640 km. (Figure 6).

The long-term lateral movement monitoring at the bridge approach structure in perpendicular and parallel directions to the highway revealed that, after construction, the lateral movement is small and could contribute to the vertical settlement of only 0.007 to 0.03 m (assuming there is no volume change due to shear flow). (Vardhanabhuti et al. 2010)
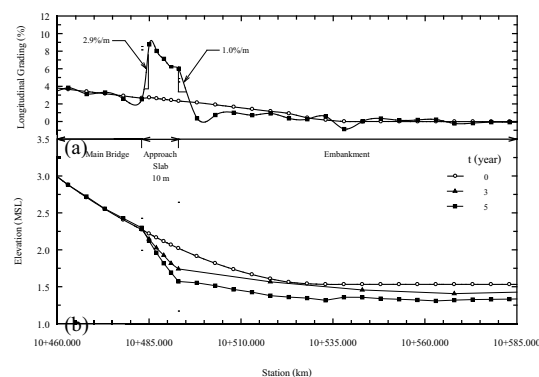

Figure 4. Klong Song bridge between 10+460 to 10+585 km. (a) Longitudinal grading, (b) Surface elevation (MSL) from as built drawing and measurement record.
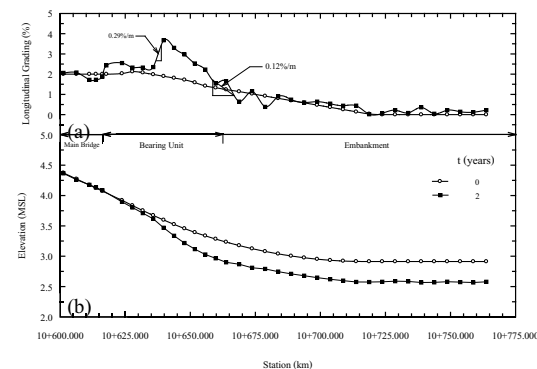

Figure 5. Klong Bang Ta Nai bridge between 10+600 to 10+775 km. (a) Longitudinal grading, (b) Surface elevation (MSL) from as built drawing and measurement record.
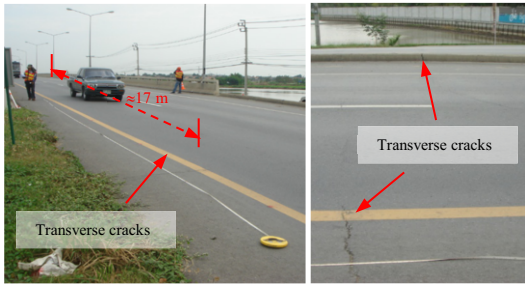
Figure 6. Transverse crack due to differential settlement.

4. Settlement Analysis of Bridge Approach Structure

One-Dimensional consolidation theory (Terzaghi, 1923, 1943) and Elastic theory were used for settlement analysis of cohesive soil and granular soil, respectively (Saowiang, 2009; and Vardhanabhuti, 2010). Figures 7 and 8 represent geotechnical parameter and load applied to the foundation for Klong Song bridge, and Klong Bang Ta Nai bridge, respectively. Vertical stress distribution from the pile to subsoil was analyzed using an equivalent foundation approach (Terzaghi and Peck, 1948) and the applied load was assumed to be a strip load. An assumption of no contact pressure between the slab and soil, and no soil structure interaction were applied.

Figure 9 shows the result of vertical stress distribution under approach slab on pile of Klong Bang Ta Nai bridge. There are apparent changes in vertical stress distribution in the very soft to soft clay layer and the medium to fine sandy clay which locate at 14 m to 18 m and 42 m to 46 m from the bridge abutment, respectively. These are due to the change in transferring load behavior, including end bearing pile to friction pile, and friction pile to shallow foundation, respectively. Furthermore, there are a large difference in compression index (c_c) and soil layer thickness. For example, in case of Klong Bang Ta Nai bridge, the c_c value of very soft to soft clay is 4.1 time that of medium fine to medium sandy clay.

For settlement rate analysis, it is assumed that the consolidation process starts immediately during 2-year construction period. Double drainage boundary is applied for dense sand layer and weathered crust layer (or fill material). The difference in coefficient of consolidation (c_v)

is taken into account by using equivalent thickness approach as shown in Figures. 7 and 8, and Eq. (1) (Barden and Younan, 1969; NAVFAC DM7-1, 1982)

$$H' = \sqrt{c_{v1}} \sum_{j=1}^{n} \frac{H_j}{\sqrt{c_{vj}}}$$ (1)

in which H' = equivalent layer thickness, H_j = the thickness of layer j, c_{v1} = Coefficient of Consolidation of reference layer, c_{vj} = Coefficient of Consolidation of layer j.
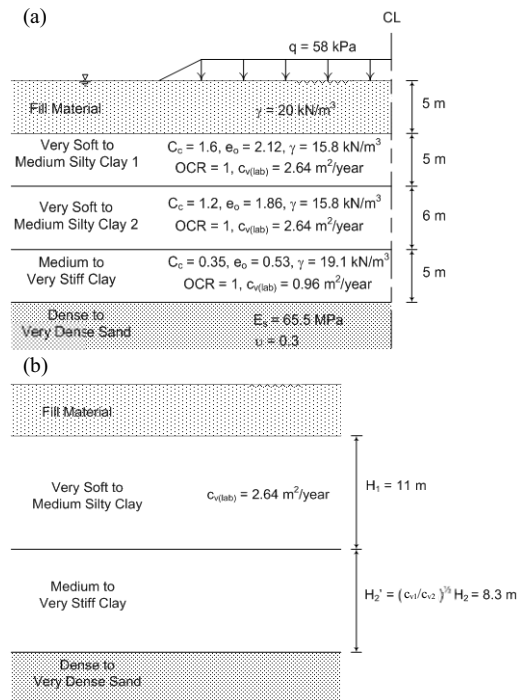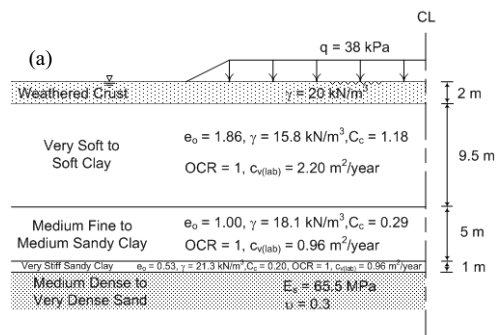

Figure 7. Subsoil condition at Klong Song bridge (a) parameters for settlement calculation, (b) change in soil layer thickness for rate for settlement calculation. (Saowiang, 2009; Vardhanabhuti, 2010)
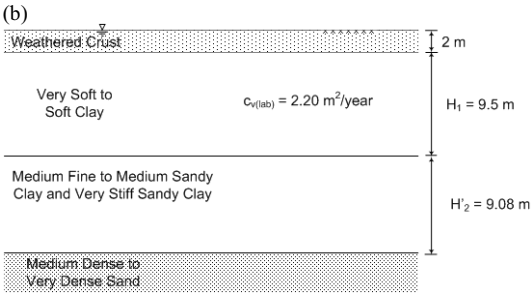
(b)

Figure 8. Subsoil condition at Klong Bang Ta Nai bridge (a) parameters for settlement calculation, (b) change in soil layer thickness for rate for settlement calculation. (Saowiang, 2009; Vardhanabhuti, 2010)

Figure 10 presents the settlement data observed in the field ($S_{observed}$) and the analysis result ($S_{predicted}$), assuming coefficient of consolidation in the field [$c_{v(field)}$] equal to that determined form the laboratory [$c_{v(lab)}$]. It reveals that at t = 7.17 years (Klong Song bridge), and t = 4 years (Klong Bang Ta Nai bridge), the $S_{predicted}/S_{observed}$ is equal to 1.0 and 0.44, in respective order. The $S_{observed} > S_{predicted}$ value could be due to $c_{v(lab)} < c_{v(field)}$ and influence of traffic volume and effect of dynamic load, i.e. impact from truck load.

5. Interaction between Relief Pile Foundation and Approach Slab

The beam on elastic material model (Winkler, 1876) was used to represent the interaction of foundation and the approach slab, as shown in Figure 11. The spring stiffness of pile and embankment foundation is determined from modulus of subgrade reaction (k_s) and the width of the load area. The k_s value was calculated from tangent modulus method (Janbu, 1963) and consolidation test results (Saowiang, 2009). For determination of shear and moment distribution in the approach slab, the k_s values were adjusted until the analysis settlements are equal to the observed settlement.

For Klong Bang Ta Nai bridge, the result show that at a distance of 14.5 m - 18.5 m from the bridge foundation, the shear force and moment are higher than the allowable shear and cracking moment, as shown in Figure 12. These high shear force and moment could result in cracking of approach slab which is in agreement with the field observation and vertical stress analysis
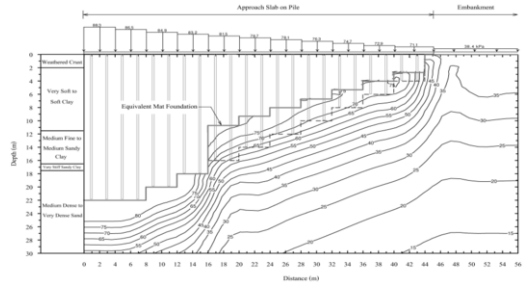

Figure 9. Vertical stress distribution underneath approach slab on pile, Klong Bang Ta Nai bridge.
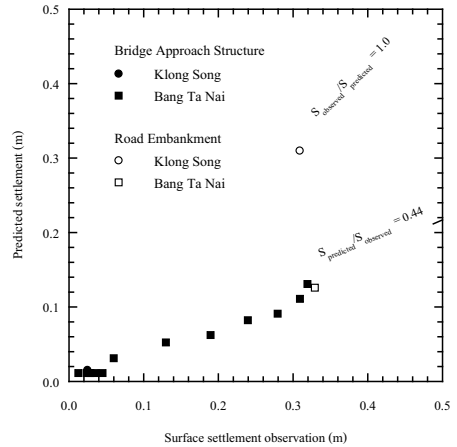

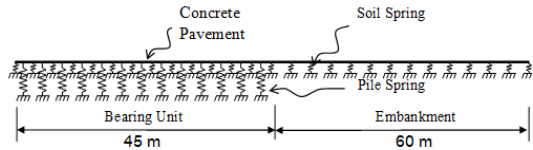**Figure 10.** A comparison between observed settlement and predicted settlement.

Figure 11. Beam on elastic material model for Klong Bang Ta Nai bridge.
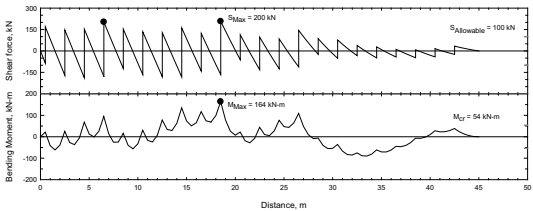

Figure 12. Shear and moment distribution along bridge approach slab of Klong Bang Ta Nai bridge.

6. Summary

Field observation and settlement analysis results of two bridge approach case studies in Bangkok and vicinities show that

1) The approach slab on pile could reduce differential settlement better than approach slab on ground. One dimensional consolidation theory (Terzaghi, 1923, 1943) and Elastic theory utilizing equivalent foundation approach (Terzaghi and Peck, 1948) could fairly predict the settlement magnitude after the construction and $S_{observed}/S_{predicted}$ is in the range of 0.44 to 1.0

2) Although the approach slab on pile is utilized, differential settlement still occurs, especially at the connection between bridge and highway embankment and the transition zone where the pile tip is in soft soil layer and stiff soil layer. The main mechanisms are (i) the change in vertical stress distribution in Soft Bangkok Clay layer due to the change in pile behavior, bearing pile and friction pile, (ii) the soil layers have a large difference in compression index (c_c) and layer thickness.

3) The back analysis of shear and moment distribution using beam on elastic theory show that the predicted crack location of the concrete approach slab is correspond to the field observations, including transverse crack on the pavement and barrier and apparent change in the longitudinal slope.

4) The change in longitudinal slope could be used to define the location of differential settlement problem. Based on study observation, when $\Delta S/\Delta L$ is larger than 2%, the driver has to reduce the speed for safety, and minimize the impact between bottom of bumper and road surface.

7. Acknowledgement

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