REACTIVATED SETTLEMENT OF AN OLD MONUMENT FOUNDED ON BANGKOK CLAY

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SYNOPSIS

A number of possible causes of reactivation of settlement of the 165-year old Reclining Buddha Image of Po Temple were investigated. The differential settlement of the 46-m long non-uniform load structure increased significantly by 115 mm during the last twenty years bringing a total to 405 mm. Investigations revealed a big variation in groundwater pressure below the structure. This non-uniform groundwater pressure in the underlying subsoils was considered to be the result of groundwater drawdown from recent deep well pumping and natural recharge from the nearby river. The development of the non-uniform groundwater drawdown brought about non-uniform consolidation of the subsoils resulting in a redevelopment of the differential settlement in the area. Settlement monitoring data and consolidation calculation confirmed this hypothesis.

INTRODUCTION

The image of the Reclining Buddha of Po Temple in Bangkok is one of the most prestigious and sacred national monuments of Thailand. This huge, gold-plated masonry structure, 46 m long and 5 m wide, was constructed more than 160 years ago in a swampy land, 150 m from the bank of the Chao Phraya river next to the world famous Grand Palace. The image is placed on a 1.3 m high pedestal in the central part of a brick building (wiharn). The wiharn's floor is in turn elevated 1.3 m above the present ground surface. Both structures are founded on a mat foundation made of brick and timber log grillage. Below the pedestal the foundation extends about 3 m below the ground surface in the soft Bangkok clay. According to the record the land was backfilled about 40 years prior to the construction of the image. The layout and profile of the image are shown in Fig. 1. The image is 5 m high in the foot side but 15 m high with a wider base in the head side resulting in a big difference in dead load intensity along its length. Presently, a large differential settlement exists along the pedestal and wiharn floor which is undoubtedly attributed partly to this non-uniform load intensity imposed on the underlying soft clay.

Although the image was constructed a long time ago, a pronounced rate of differential settlement was observed again recently resulting in cracking of the image. In 1973, the differential settlement along the image between its head and foot sides

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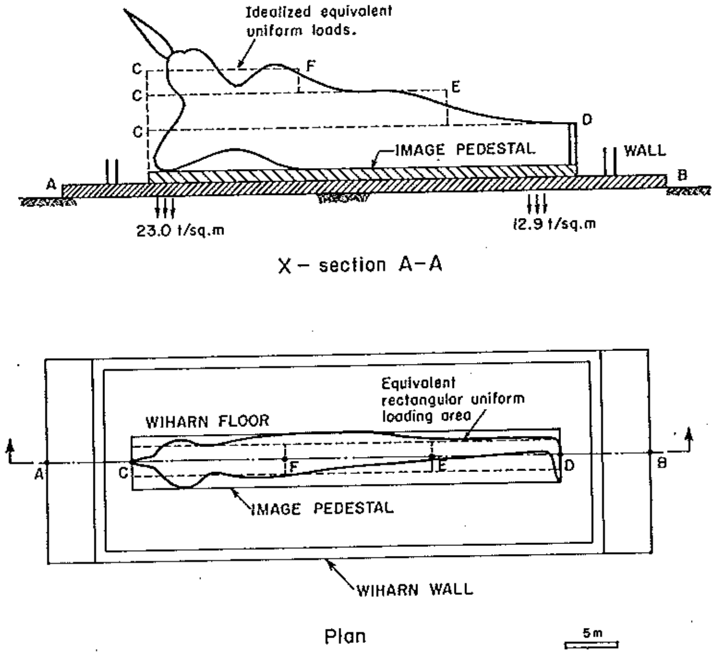

Fig. 1 Profile and Plan Layout of the Buddha Image.

was recorded at 290 mm (Nelson & Viranuvuth, 1973). A slightly smaller amount of differential settlement also existed along the floor of the wiharn.

In 1985, the differential settlement had increased by 90 mm from the 1973's magnitude bringing it to a total of 390 mm. A network of settlement points were then installed to monitor the movements of the image, wiharn and the nearby ground areas (EGAT, 1985). Subsoil conditions underneath the entire area were investigated using six boreholes and Dutch cone tests (Fig. 2). Compressibility of the soft clay and the underlying stiff clay and its variations within the area were evaluated from oedometer tests (Sambhandharaksa, 1987).

Because post-1987 monitoring data revealed that the differential settlement still continued, a comprehensive investigation was undertaken in 1990 to determine the cause of the settlement and select appropriate remedial measures. The investigation assessed the subsoil conditions and variations, traffic induced vibrations, deterioration of the foundation materials, creep of the soft clay, deep well pumping, and fluctuation of the nearby Chao Phraya river. The contributing roles of some of these potential causes are presented herein.

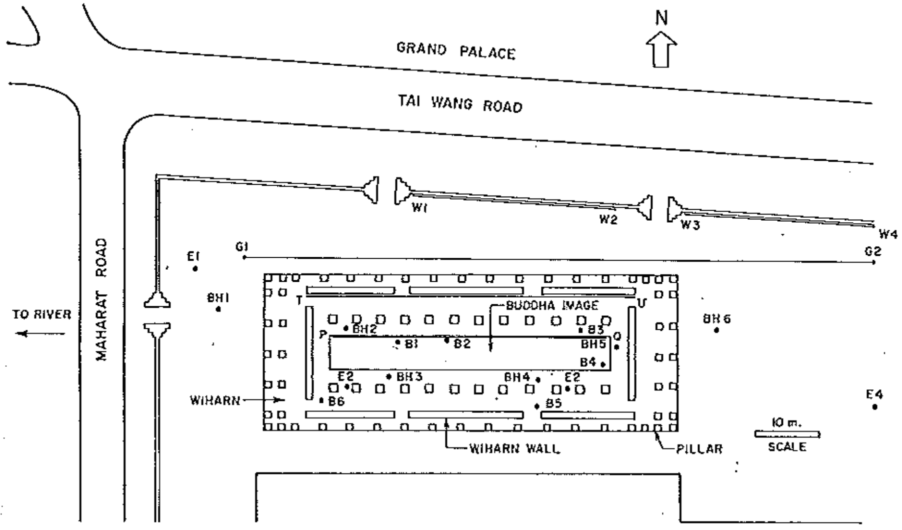

Fig. 2 Locations of Boreholes and Settlement Monitoring Lines.

SUBSOIL CONDITIONS

From additional six continuously sampling boreholes (BH1-BH6), the subsoils can be divided into 6 distinct layers, namely, i) very soft dark gray clay mixed with pieces of bricks and timbers existing below the mat foundation to depths of 3 to 5 m, ii) medium dark gray marine clay from a depth of 3 m to 12.5 m, iii) thin stiff light gray clay mixed with pebbles extending down to 13 m depth, iv) stiff grayish brown to yellow clay to a depth of 18.5 m, v) hard brown sandy clay to clayey sand partly mixed with medium blue clay to a depth of 22 m, and vi) find brown sand to a depth greater than 38 m.

The subsoil stratigraphy (Fig. 3) is relatively uniform throughout the area except for the thickness of the vary soft clay layer below the surface which is about 2 m thicker in the head side area. This layer is suspected to be an old landfill. Three distinct features are present in the subsoils as described below.

Very thin seams of silt to very fine sand exist sparsely in the medium clay layer throughout depth. However, a thick (0.5-1.0 m) seam is present from 8.5 to 9.5 m depth throughout the area. It was noticed that this seam is more sandy and thicker in the head side area.

A sublayer of weathered clay exists within the thick layer of stiff grayish brown clay layer throughout the area at 14-16 m depth. The soil contains alternating very thin lenses of weathered silty clay and reddish lateritic fine sand. The presence of fine sand and silt in this weathered part of the layer provides a permeable seam sandwiched in stiff clay layer.

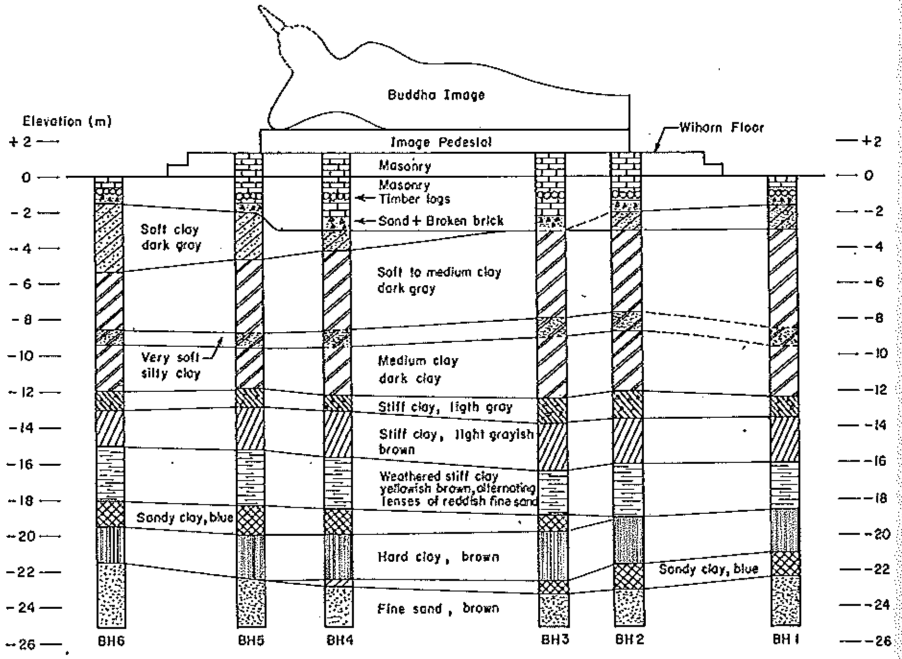

Fig. 3 Subsoil Profile underneath the Buddha Image.

Numerous slicken-sided shear surfaces were found throughout the whole depth of the vary soft and medium clay over the entire area underneath the structures. The presence of the surfaces was an evidence of previous shear failure of the soils, probably from the undrained loading from the weight of the structures during the construction. An elastic stress calculation (AIT, 1991) revealed that the induced undrained stresses in the subsoils by the weight of the structure exceeded the original undrained shear strength of the soils throughout the depth of the soft and medium clay. The calculated stresses were close to the present undrained strength of the clay as determined from consolidated undrained compression triaxial test results. The presence of the slicken-sided surfaces makes the clay locally much weaker. Several clay specimens containing these shear surfaces failed at low stresses in the triaxial tests.

Unconsolidated undrained triaxial test results (Fig. 4) clearly showed that the undrained shear strength of the clay was higher in the area underneath the image than that in the outside area. This was thought to be the result of the post construction consolidation of the clay from stress increases by structural loading.

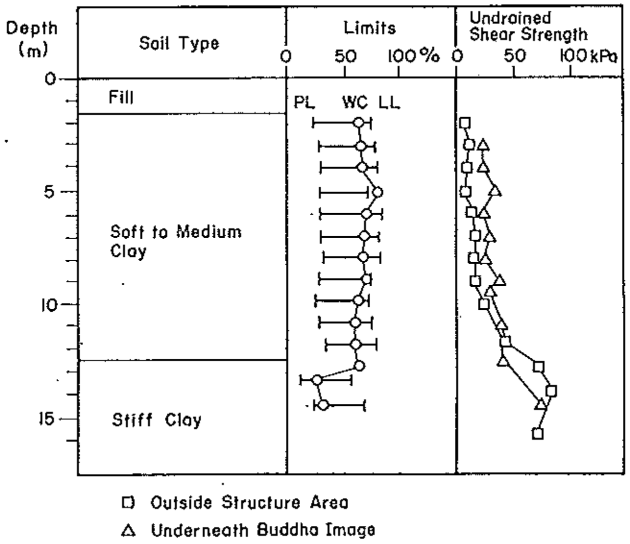

Fig. 4 Index Properties and Undrained Shear Strength of Subsoils.

The ranges of the state of stresses that presently exist at various depths in the soft clay layer below the head and foot side of the image are outlined in Fig. 5. These stresses are calculated from the weight of the structure using an elastic solution assuming an equivalent stack of uniform loads (Fig. 1) on a flexible foundation. It can be seen that in the head side area the soft to medium clay layer is presently subjected to vary high stress levels as compared to its strength. On the contrary, the stress levels are not so high in the foot side area.

No significant difference in condolidation properties (Table 1) of each soil layer between the head and foot side areas was detected except that the OCR of the soft clay layer was around 1.0-1.2 in the head side area while it is 1.8-2.2 in the foot side area. Outside the loading area the OCR of the clay in 1.9-2.3.

TRAFFIC VIBRATIONS

Peak ground particle velocity induced by traffic recorded just outside the wiharn was as high as 0.9 mm/sec. This peak particle velocity corrresponded to a peak acceleration of 0.006 g for a harmonic vibration. Judging from previous studies

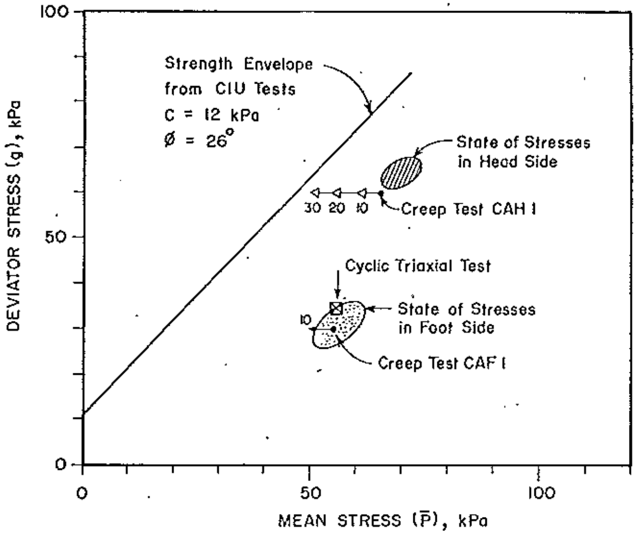

Fig. 5 Shear Strength Envelope of Soft Clay and Existing States of Stress underneath the Buddha Image.

Table 1 Consolidation Properties of Subsoils
A) Underneath the Structures

	BH 2 (FOOT SIDE)				BH 5 (HEAD SIDE)				
Depth m	*OCR*	e_0	$\frac{C_r}{1+e_o}$	$\frac{C_c}{1+e_o}$	*OCR*	e_o	$\frac{C_r}{1+e_o}$	$\frac{C_c}{1+e_o}$	Remark
4	2.20	1.656	0.045	0.303	0.94	1.760	0.036	0.325	Soft Clay
5.5	1.77	1.925	0.023	0.385	1.20	1.830	0.039	0.411	Soft Clay
7.5	1.85	1.636	0.038	0.302	1.02	1.430	0.052	0.273	Soft Clay
14	1.96	0.618	0.041	0.154	1.78	0.740	0.042	0.092	Stiff Clay

(Satavanija & Nelson, 1971, Ha, 1983), cyclic stresses induced by this level of vibration on the soft Bangkok clay subjected to the typical range of static effective overburden stress (shallow than 10 m) would not have any adverse effect on the strength of the clay. Nevertheless a series of cyclic undrained triaxial tests were conducted on samples of the soft clay from underneath the wiharn. In the tests, cyclic stresses corresponding to three values of peak particle accelerations (0.02 g, 0.06 g and 0.12 g) were applied to samples that had been anisotropically consolidated at the states of stresses corresponding to those presently existing at various depths underneath the foot side area of the image.

The test results indicated that even for the worst cyclic stresses adopted in this test series (i.e. particle acceleration of 0.12 g on a specimen consolidated at the largest anisotropic stress: $\bar{\sigma}_1 = 80$ kPa and $\bar{\sigma}_3 = 45$ kPa, shown in Fig. 5) tha application of cyclic stresses up to 10000 cycles did not weaken the subsequent static undrained strength (Fig 6). Therefore, traffic induced vibration was excluded as a cause of the settlement.

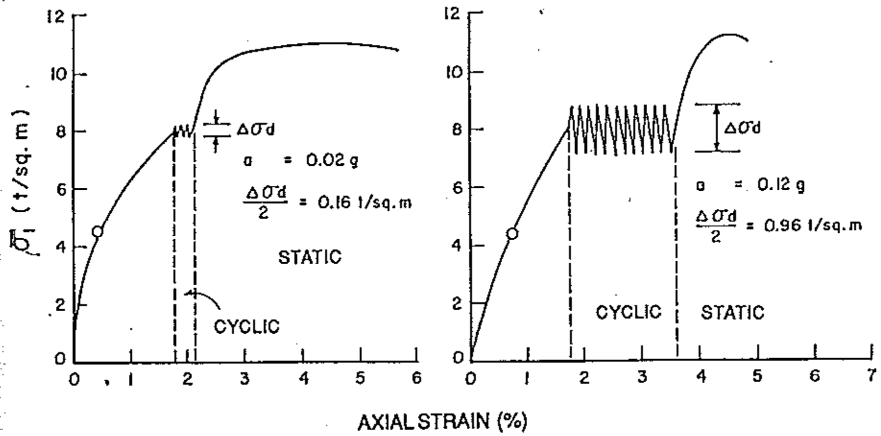

Fig. 6 Stress-Strain Relation of Soft Clay from Cyclic Triaxial Tests, $\bar{\sigma}_3 = 4.5$ t/sq.m.

CREEP OF SOFT CLAY

Creep of the soft clay induced by seasonal fluctuation of shallow groundwater table was also investigated as a potential cause of the reactivated settlement. Groundwater level fluctuation was between 0.5-1.0 m (up to 10 kPa fluctuation of hydrostatic porewater pressure).

A number of triaxial creep tests were conducted on the soft clay samples. The first series (multi-step isotropically consolidated undrained creep tests following the method suggested by Semple (1973)) was to investigate the undrained creep properties. The test results showed that the "creep parameter" (defined by Semple (1973) as the slope of the linear relationship between axial strain and elapsed time in a log-log scale) of the soft clay was in the range of 0.03-0.06. This does not represent an extraordinarily high creep potential of the clay (Mesri et al, 1981).

The second series was to investigate the response of the clay to an increase in porewater pressure. The clay specimens were initially equilibrated at two anisotropic consolidation stress fields, i.e. the high and low shear stresses (tests CAHI and CAFI in Fig. 5), simulating the stress conditions existing underneath the image in the head and foot side areas. The combined effect of swelling and drained creep response to an increase in porewater pressure by 10 kPa resulted in a very minor increase in axial strain with time for both initial stress conditions. The creep parameter was smaller than 0.004. For test CAHI (the state of stress corresponded to that existing below the head side) the specimen did not start to show significant creep response until a 30 kPa of porewater pressure increase was applied (Fig. 7). Therefore, at was concluded that creep of the soft clay was not a significant factor contributing to the continuing differential settlement of the image.

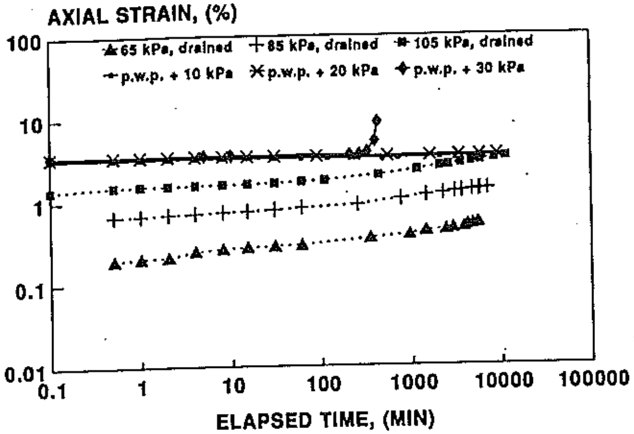

Fig. 7 Axial Strain-Elapsed Time Relationship from Anisotropically Consolidated, Drained Creep Test of Soft Clay, Test CAH 1.

DEEP WELL PUMPING

Bangkok land elevation monitoring data during the last 60 years indicates that the area of Po Temple has subsided by as much as 580 mm (AIT, 1981 and RTSD, 1989); 220 mm of which occurred between 1978 and 1989. During the peak of deep well pumping, 1978 to 1981, the area was subsiding at the rate of 30-40 mm/year. After 1984, deep well pumping in the inner Bangkok area had been substantially reduced to almost none at the present. Consequently, the rate of land subsidence in the vicinity of Po Temple has decreased to only a few millimeters a year but still continues to develop. In addition the recent land subsidence monitoring data suggests that up to 55% of the total amount of land surface subsidence was from the compression of clay layers shallower than 20 m (AIT, 1991).

Piezometric pressure distribution with depth in the subsoils underneath the Buddha image observed from a network of open-stand pipes with AIT type piezometer heads installed in the latest investigation is summarized in Fig. 8. There is a marked difference in the magnitude of piezometric pressures at depths deeper than about 8 m between the head side and foot side areas. The drawdown in the head side area was similar to those typically observed throughout Bangkok area due to deep pumping (AIT, 1981 and Ng, 1983). However, it was much smaller in the foot side area. The reason for this big difference in the drawdown within a short distance of 46 m along the length of the image is not yet clear. However, it is considered that the groundwater levels may be influenced by recharge from the Chao Phraya river located just 150 m away from the foot side (Fig. 9).

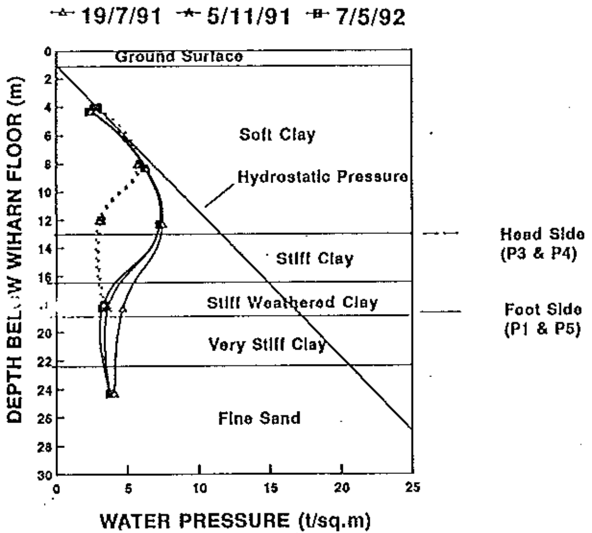

Fig. 8 Difference in Groundwater Conditions between the Head and Foot Sides of the Buddha Image.

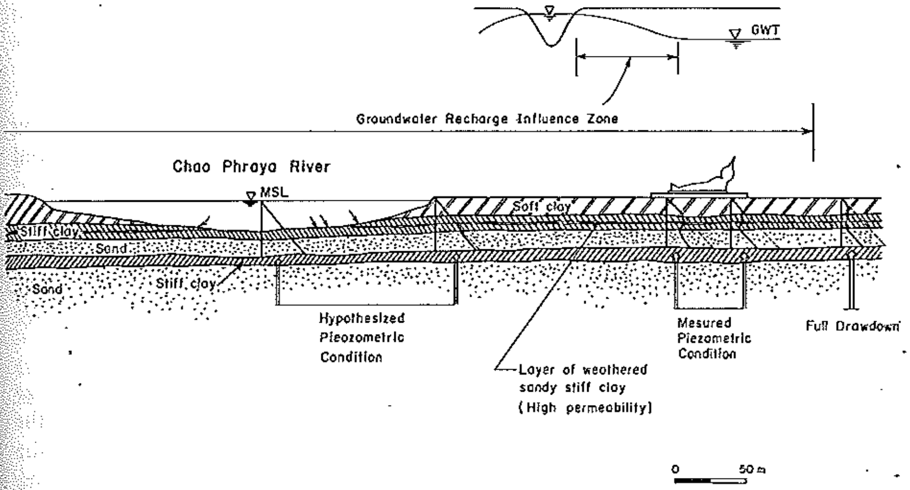

Fig. 9 Hypothesized Groundwater Condition in the Area of the Buddha Image.

SETTLEMENT RECORD

Settlement monitoring of the Buddha image began in 1985 and revealed a continuing increase in settlement but at a decreasing rate beneath all parts of the structure and outside ground surface as summarized in Fig. 10. The magnitudes of the settlement shown in the figure were in reference to a 20-m deep benchmark located 400 m away. The benchmark must have also undergone some deep settlement itself. However, subsidence of the benchmark during the monitoring period was not recorded.

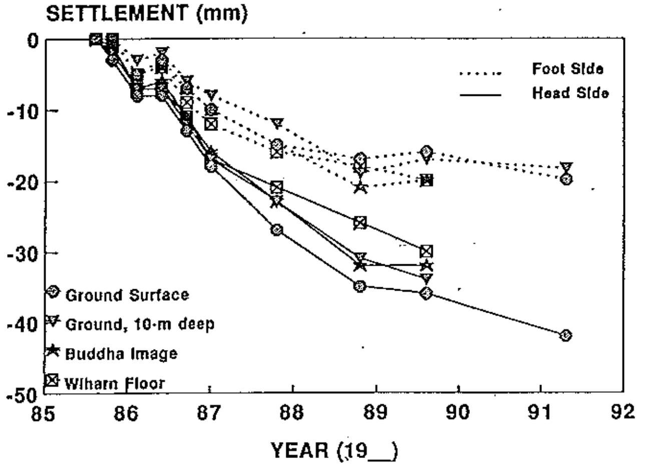

Fig. 10 Increases in Settlement of Various Parts of Structure and Ground.

All settlement points showed greater rates of settlement in the head side area than in the foot side area resulting in the continuing increase in the differential settlement as shown in Fig. 11. The differential settlements of the structures and outside ground surface showed a similar trend of a decreasing rate with time that almost leveled off at present.

The data revealed that the ground surface outside the loading area from the weight of the structure continued to settle at a similar rate to those of the structures in both the head side and the foot side (Fig. 10).

Deep ground settlement points installed in the head side area of the image (EGAT, 1987) showed only a slightly smaller settlement than those recorded by the corresponding surface settlement points (Fig. 10). This indicated that most of the recorded surface settlement was from consolidation of soil layers deeper than 10 m, not the shallow soft clay layer. Multiposition borehole extensometers were just installed a year ago to verify this but the data recorded is still too small.

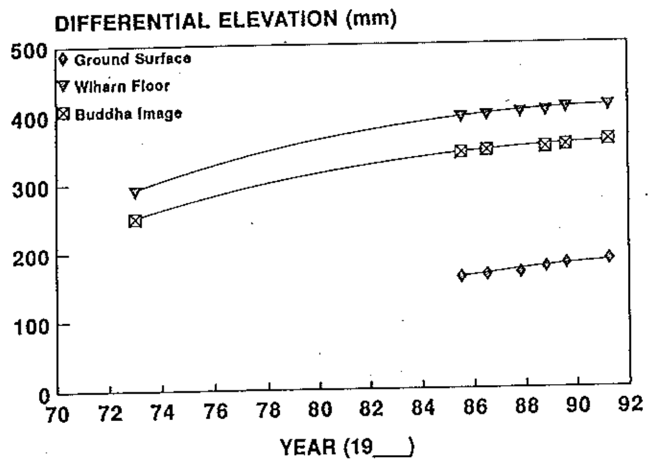

Fig. 11 Increases in Differential Settlement of Various Parts of Structure and Ground.

CAUSES OF THE SETTLEMENT

The value of coefficient of consolidation of the clays indicates that the primary consolidation of the soft clay as a result of the weight of the structures must have been completed not more than 30 years after the construction. Any secondary compression from the effect of the dead load that might exist at present would not be significant (AIT, 1991).

It is considered that the reactivated settlement of the Buddha image during the last 20 years is linked to the recent groundwater drawdown induced by deep well pumping. However, the effect of recharge from the nearby Chao Phraya river of the structure has tended to reduce the amount of drawdown underneath the structures. The settlement was not thought to be directly related to the existence of the shallow soft clay layer despite the fact that the clay underneath the image contained existing slicken-sided shear surfaces throughout the layer and was subjected to a high shear stress level in the head side area from the non-uniform dead load of the image along its length. This was because the ground surface outside the loading areas from the structures also showed a similar pattern and manitude of settlement to those of the image and wiharn.

A calculation of the differential settlement between the two extreme points in the head and foot of the Buddha image gives values comparable with the actual measured values for both dead weight consolidation from the observed non-uniform piezometric level (Table 2).

Table 2 Consolidation Properties of Subsoils
B) Outside Loading Area from the Structures

	BH 1 (FOOT SIDE)						BH 6 (HEAD SIDE)						
Depth m	OCR	e_o	$\frac{C_r}{1+e_o}$	$\frac{C_c}{1+e_o}$	k cm/sec (10^{-8})	C_α ($x10^{-3}$)	*OCR*	e_o	$\frac{C_r}{1+e_o}$	$\frac{C_c}{1+e_o}$	k cm/sec (10^{-8})	C_α ($x10^{-3}$)	*Remark*
4	1.93	1.92	0.032	0.250	1.3-4.7	3.47-19.9	2.22	2.020	0.027	0.270	0.8-7.3	0.56-8.97	Soft Clay
5.5	2.27	1.97	0.056	0.369	1.3-3.3	1.81-10.29	2.15	1.760	0.048	0.437	0.4-1.3	2.34-13.46	Soft Clay
7.5	2.10	1.57	0.030	0.323	1.6-4.9	0.96-12.58	2.30	1.516	0.041	0.303	0.5-0.8	1.94-12.89	Soft Clay
9.5	2.80	2.09	0.044	0.213	1.1-4.2	1.03-9.34	0.47*	1.880	0.040	0.219	1.3-3.3	9.23-13.83	Soft Clay
14	1.71	0.77	0.047	0.126	0.1-0.3	2.33-6.28	1.74	0.631	0.037	0.094	0.2-0.5	1.73-2.65	Stiff Clay

Actual increase in differential settlement between 1973-1990	115 mm
Actual total differential settlement at present	405 mm
Calculated differential settlement due to consolidation from dead load of structure	303 mm
Calculated differential settlement from the observed non-uniform drawdowns	148 mm
Total calculated differential settlement	449 mm
Land subsidence in nearby area between 1978-1987	220 mm
Estimated compression of the first 20-m soil layers between 1973-1985 based on land subsidence measurement data	+ 110 mm

* Sandy Clay

Most of the surface settlement resulted from consolidation of the deep soil layers, therefore any possible adverse behavior of the soft clay layer such as creep or weakening caused by traffic vibrations should not be significant. This is substantiated by the settlement that also developed in the foot side area which should not be sensitive to either creep or vibration induced settlement as the soft clay is only subjected to relatively low shear stresses.

At present, no remedial measures have been undertaken due to two reasons. Firstly, the current rate of settlement is very small and has shown a levelling off trend. Secondly, the integrity of the foundation of the structures is not know yet. Thus, an attempt to stabilize the ground might damage the structures.

CONCLUSIONS

A Number of possible causes of the reactivation of settlement of the 165-year old reclining Buddha image founded on Bangkok clay were investigated. The following conclusions were drawn.

i) The recent settlement of the image was triggered by groundwater drawdown brought about by deep well pumping. The non-uniform drawdown which occurred beneath a laterally persistent soft clay layer considered to be related to the effect of natural recharge from the nearby Chao Phraya river.

ii) Greater drawdown occurred in the head side area of the image coinciding with a larger increase in settlement. However, the observed increase in the differential settlement of the image is not related to its non-uniform dead load intensity because the adjacent ground area and a nearby uniform-weight structure also experienced a similar pattern of differential settlement.

iii) The recent settlement of the image is not related to creep or weakening of the soft clay by vibration or shallow groundwater fluctuation. This was confirmed by the laboratory studies on the soft clay. The traffic induced vibration was too low to influence the strength of the soft clay. Even under the relatively high shear stress levels existing beneath the head side area of the image, the soft clay showed insignificant creep response to an increase in porewater pressure corresponding to the range of groundwater level fluctuation. Most of the observed settlement was from consolidation of soil layers below the soft clay.

iv) Similar rates of settlement occurred beneath the structures and outside ground surface for each side of the image. The rates have decreasing with time for the last 20 years and almost level off at present.

ACKNOWLEDGEMENTS

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