Geotechnical Aspects of Underground Construction in Soft Ground, Kusakabe, Fujita & Miyazaki (eds)
© 2000 Balkema, Rotterdam, ISBN 90 5809 1 066

Experimental study of heaving in a cofferdam on soft ground

T. Kawasaki
Department of Civil Engineering, Hachinohe Institute of Technology, Japan
Y. Shioi
Construction and Environmental Engineering Laboratory, Hachinohe Institute of Technology, Japan

ABSTRACT: A series of experimental studies using 2 rigid wall cofferdam models in a test box filled with bentonite on sand mat were conducted to study heaving and reasonable countermeasures. Heaving was generated by excavation inside models, uniform surcharge on the surface and several levels of ground water. We found that it is more reasonable to evaluate heaving by the sustaining capacity at the bottom excavated than by circular slip because heaving is plastic flow. Through a series of experiments, we presume that countermeasures outside a cofferdam are more effective than inside, and heaving is affected by the ground water level.

1 INTRODUCTION

Heaving is a problem in excavation in a cofferdam with sheet piles on thick soft ground. It increases excavation volume, inclines sheet piles inward, risks collapse of the cofferdam, settle the surrounding ground, and damages neighboring structures. Measures such as using more rigid sheet piles, extending the embedded length of sheet piles, and improving ground inside the cofferdam, are popular in Japan, but not prevent influence on the sheet piles and surrounding ground.

To calculate the safety factor preventing heavings, several formulas have been proposed as shown in Figures1-3.

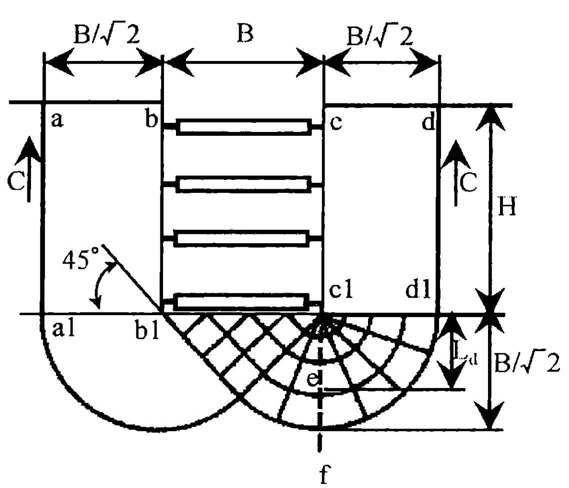
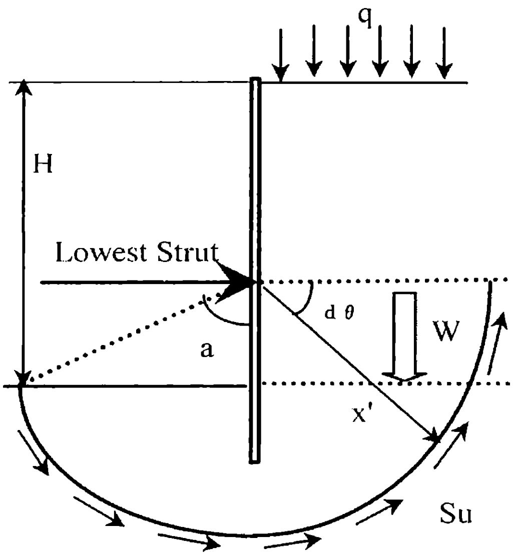


Figure 1. Method of Terzaghi & Peck.

Formula of Terzaghi & Peck

$$F = \frac{q_d}{p_v} = \frac{5.7c}{\gamma H - \frac{\sqrt{2}cH}{B}} \tag{1}$$



$$F = \frac{M_r}{M_d} = \frac{x'\int_0^{\frac{\pi}{2}+a} Su(x'd\theta)}{W\frac{x'}{2}} \qquad (a<\pi/2)$$

Figure 2. Method of Architectural Institute of Japan.

Formula of Architectural Institute of Japan

$$F = \frac{M_r}{M_d}$$

$$= \frac{x'\left(\frac{\pi}{2} + a\right)x' su}{(\gamma H + q)_{x'}\frac{x'}{2}} = \frac{(\pi + 2a)su}{\gamma H + q} \qquad (2)$$

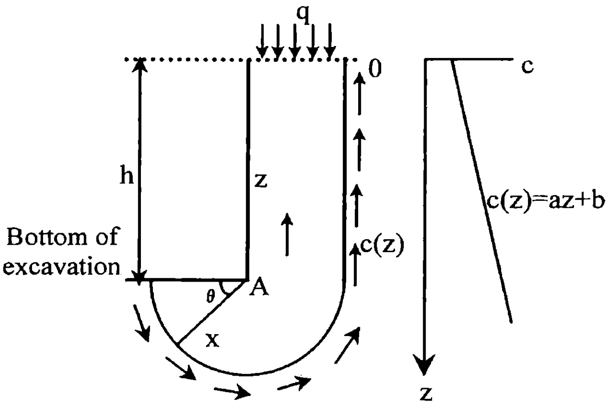


Figure 3. Method of Japan Road Association.

Formula of Japan Road Association

$$F = \frac{M_r}{M_d}$$

$$= \frac{2}{\gamma h + q}\left\{(ah + b)\pi + 2\sqrt{a^2h^2 + 2abh}\right\} \qquad (3)$$

where F: safety factor
q_d: sustaining capacity at bottom (Pa)
p_v: acting force at the bottom (Pa)
c: cohesion of soil (Pa)
γ : unit weight of soil (kN/m^3)
H,h: excavation depth (m)
B: cofferdam width (m)
M_r: rotational moment by acting force (kN m)
M_d: resistant moment (kN m)
x,x': arm length from lowest strut (m)
su: shear resistance along circle (Pa)
z: depth coordinate (m)
q: surcharge on the ground surface (Pa)
a,b: cofficients of ground cohesion

Tschebotarioff, Bjerrum & Eide, Finn, and others also have proposed formulas. These formulas are based on plastic equilibrium theory, and can not be used to calculate the deformation of ground and sheet piles. Heaving deforms sheet piles and this deformation further aggravate heaving.

Further study is thus required to ensure cofferdam safety using sheet piles and to prevent surrounding settlement accompanying cofferdam excavation.

2 PURPOSE AND METHODS

2.1 *Purpose*

To set up a reasonable design for heaving generated at a cofferdam with sheet piles, we studied the heaving mechanism through a series of laboratory tests since the on-site observation is difficult.

2.2 *Test overview*

First, we studied the heaving mechanism using rigid-wall models (Figure 4). The steel box used in tests was 2.4 m x 1.2 m x 1.3 m, with two glass walls and could hold ground water at any height to act as uplift.

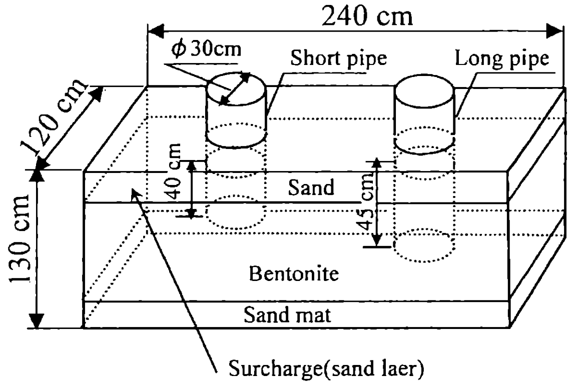


Figure 4. Box and models of cofferdam for heaving test.

The box was filled with bentonite to a depth of 90 cm, as very soft ground, on a sand mat 10 cm thick. The resistance of bentonite was measured with a special cone penetrometer made for this test (Figure 5).

2 rigid-wall cylinder models of vinyl-chloride with a diameter of 30 cm and lengths of 40 cm (short) and 45 cm (long) were installed on the soft bentonite and fixed with binding and steel beams at the top of the box.

Heaving was generated by inner excavation in the model, the uniform surcharge of sand layer on the surface, and several levels of ground water. Upheaval at the inner bottom in the model was measured at the center with a dial gauge. Settlement of the surface around the model and such measurements as sand layer thickness, were checked at each point with a scale.

The deformation of inside ground was induced with soft vinyl pipes (hoses) embedded up to the bottom of bentonite around models before the test and stiffened by liquid plaster added after the last

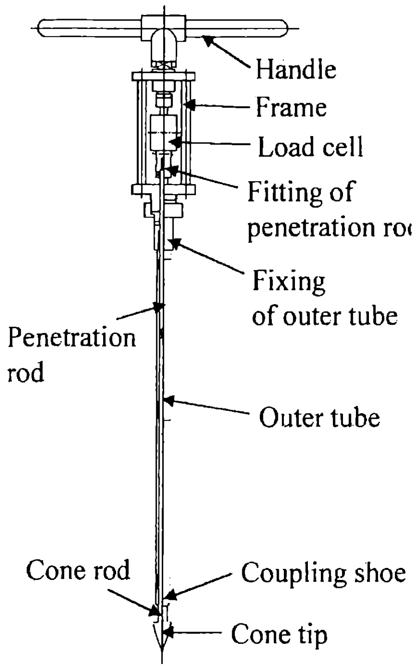


Figure 5. Cone penetrometer.

loading.

A few steel bars instead of piles were stuck around the model to prevent heaving. They are expected two functions to sustain the weight of surrounding ground by their skin friction and to resist horizontal deformation of the ground by their rigidity.

3 RESULTS

3.1 *Comparison of embedded depth*

Figure 6 compares upheaval in the short and long pipes. Depth excavated was 30 cm and embedded depth was 0 cm and 5 cm. Short-pipe upheaval exceeds long-pipe upheavl over time. Figure 7 shows ground resistance. Surface settling was very small. Figure 8 shows other cases that show settling decreasing with distance.

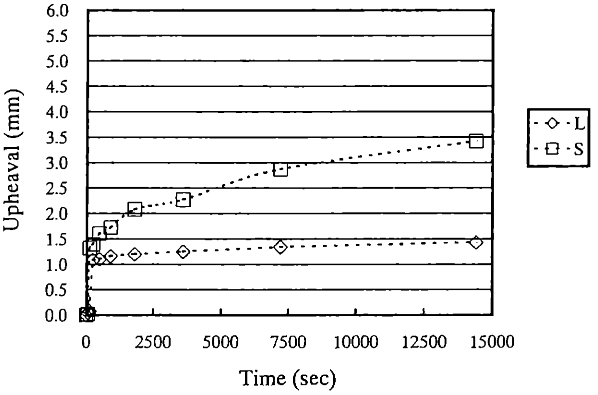


Figure 6. Upheaval in short and long model.

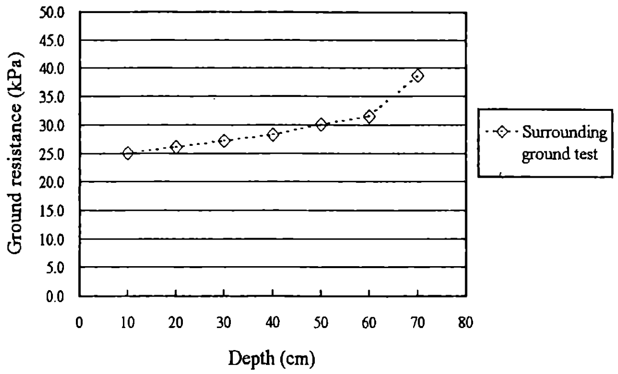


Figure 7. Mean ground resistance at surrounding ground.

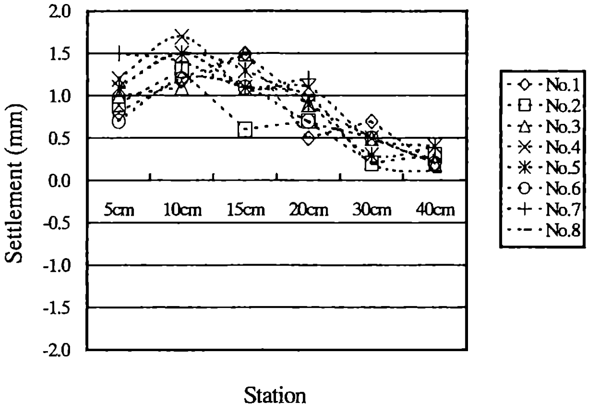


Figure 8. Settlement of surrounding ground.

3.2 *Influence of groundwater levels*

Figure 9 shows the test concept. Figure 10 shows upheavals under 4 groundwater level H. Figure 11 shows upheaval with increasing water level step by step. The ground resistance of points distributed at 15.0~20.0 kPa and surface upheaval was observed at H >100 cm.

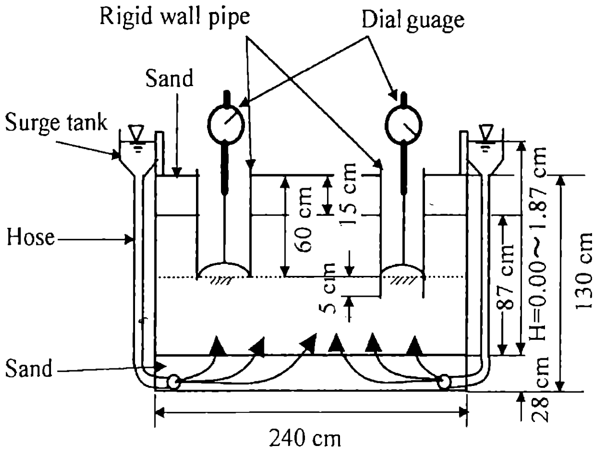


Figure 9. Scheme of uplift test.

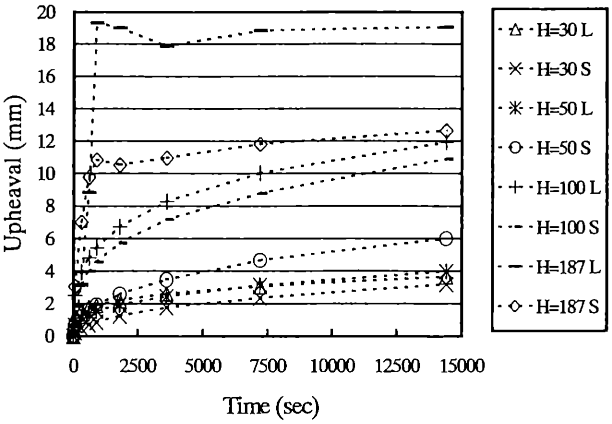


Figure 10. Upheaval by uplift (rapid application).

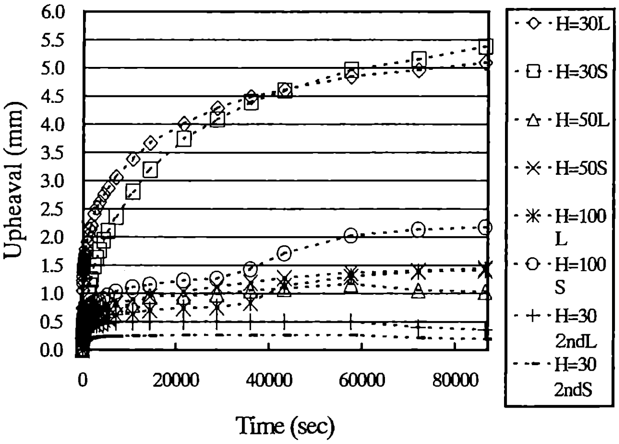


Figure 11. Upheaval by uplift (step by step application).

3.3 *Underground movements*

Figure 12 shows the positions of embedded hoses. Figure 13 compares upheaval in the 2 models. Figures 14-15 indicate the horizontal vector of underground deformation. Since the ground resistance is almost uniform at 10.0~15.0 kPa at all points, great ground movement was distributed on the lower side.

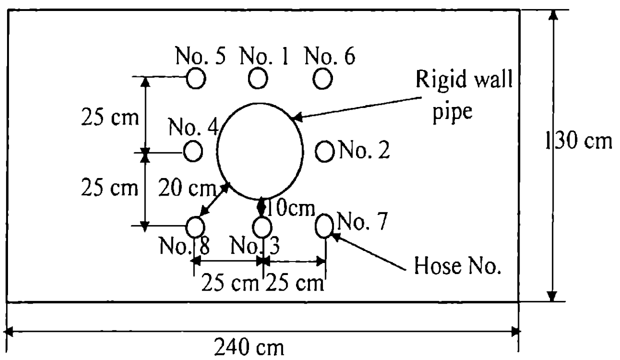


Figure 12. Position of measuring hoses for ground deformation.

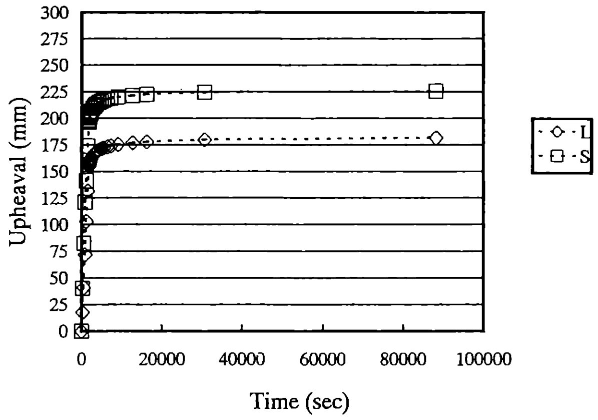


Figure 13. Upheaval at ground deformation Test.

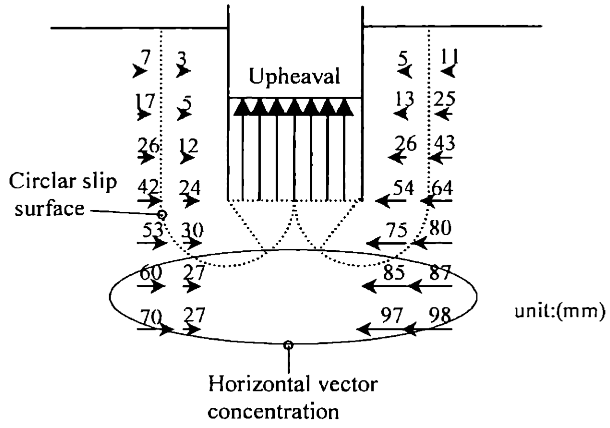


Figure 14. Movement of underground (short pipe).

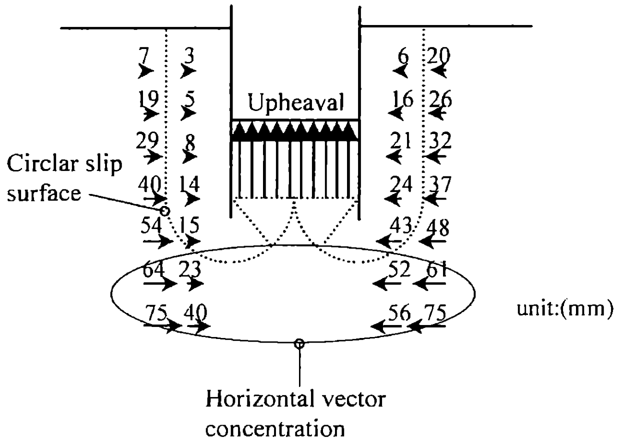


Figure 15. Movement of underground (Long pipe).

3.4 *Effect of reinforcing steel bars*

Figure 16 shows the disposition of steel bars around the 2 models. Figure 17 shows upheaval behaviors in the 2 models for the presence of steel bars. The reinforcement effect appeared early on but decreased with time.

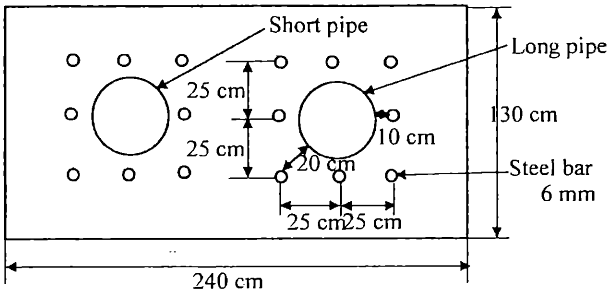


Figure 16. Position of steel bar.

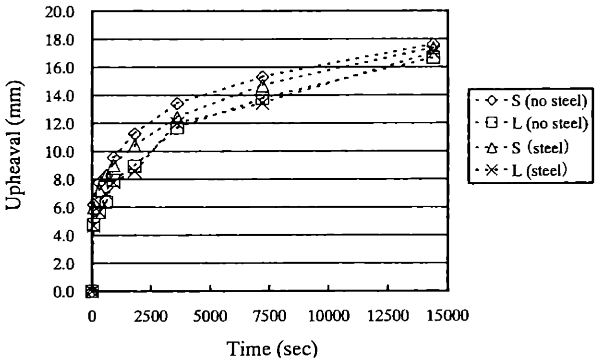


Figure 17. Upheaval at ground improvement test.

4 DISCUSSION

From Figure 6 and others, embedded depth effectively reduced the amount of upheaval but the difference is not so great. Generally, initial movement is relatively great and elastoplastic. Later movement depends on the resistance of ground and was viscoelastic. To prevent heaving we must increase soil resistance and/or to sustain the weight of surrounding ground at the excavated bottom, neglecting cohesion resistance along the depth.

Since the level of ground water and uplift strongly influence heaving, dewatering outside ground around a cofferdam is effective, although the groundwater level was not taken in account in heaving. According to Figures 10-11, though the upheaval caused with large uplift is great, but upheaval on the same uplift step by step is relatively small. This means that rapid excavation or increasing ground waterlevel is dangerous and careful excavation may reduce upheaval and promote the consolidation of soft ground.

Figures 14-15 show that ground movement by heaving extends widely and exceeds the slip circle extent. Although exact movement can not be identified with heaving because the vertical vector is not measured, it is apparent that no slip circle or logarithmic spiral slip occurs and movement is a sort of plasticflow. To prevent heaving, ground improvement outside cofferdams is desirable though the improved area becomes wider.

The reinforcing steel bars imitate piles instead of ground improvement piles. The test result was only slightly effective. The causes are induced that the number of piles was too small and the ground was too soft. Further tests are required for countering heaving.

5 CONCLUSIONS

1. Heaving is recognized as a sort of plastic flow of soft ground. To identify heaving with plastic flow, we must measure the movement of soft ground more exactly.
2. Ground improvements to increase the resistance of soil and/or to sustain the weight of surrounding ground, effectively prevent heavig.
3. It is possible to use temporary piles instead of ground improvement piles, but further tests are required to appraise their effects.
4. The level of ground water strongly affects heaving. Dewatering outside cofferdams is effective if such damage as uneven settlement does not occur in surrounding areas.
5. The amount of upheaval by the same level of ground water differed with the rapid application of uplift and the step-by-step application. It means that careful excavation is required at soft ground sites with high groundwater level.

REFERENCES

Architectual Institute of Japan 1988. *Guidelines for design and construction of cofferdams.*

G, P, Tschebotarioff 1957. *Soil Mechanics, Foundation and Earth Structures*, McGraw Hill.

K.Terzaghi & R.B.Peck 1967. *Soil Mechanics in Engineering Practice*, John Wiley & Sons, Inc.

L. Bjerrum & O. Eide 1956. Stability of Strutted Excavavation in Clay, *Geotechnique*, Vol. 6.

Japan Road Association 1987. *Earthworks for roads, Guidelines for retaining walls, culverts, temporary* work.

W. D. Finn 1963. Stability of Cuts in Clay, *Civil Engineering.*