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Cost reduction of diaphragm wall excavation using air foam

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ABSTRACT: A novel stabilizing liquid using air foam rather than bentonite clay slurry, i.e. air foam suspension, is employed in order to stabilize the trench wall surface during a diaphragm wall excavation. Air foam suspension is used to reduce the construction costs of working on an underground diaphragm wall. Air foam suspension is created by mixing the excavated soil with air foam made from a surface-active chemical agent. The performance of air foam suspension depends on its density and consistency, that is, its table flow value (TF). By comparing the trench stabilization capacity of air foam suspension with that of bentonite clay slurry in model tests, the appropriate performance of air foam suspension was confirmed. The cost evaluation of using an air foam suspension for a diaphragm wall excavation is presented.

1 INTRODUCTION

Currently, bentonite clay slurry is employed to stabilize the trench wall surface during an underground diaphragm wall excavation. However, the cost of bentonite clay is high and the construction costs of working on an underground diaphragm wall are also high due to the disposal cost of high water content bentonite clay slurry as an industrial waste.

The aim of the present study was to develop a novel liquid for use in stabilizing the trench wall surface during a diaphragm wall excavation using air foam. This liquid was developed to be employed in the Trench Cutting Re-Mixing Deep Wall (TRD) method, which is one of the most frequently used diaphragm wall construction methods in urban area. Air foam suspension is produced from a surface active chemical agent by mixing the excavated soil with air foam in the mixing plant, from which it is then conveyed to the trench wall excavation.

2 AIR FOAM SUSPENSION

The basic material used for the air foam suspension is a foaming agent known as a surface-active agent. The surface-active agent is diluted with water at a ratio of 1:20 (agent: water) by weight. The diluted surface-active agent liquid is then stirred with air to produce air foam (Fig. 1) of twenty-five times the original volume. Air foam suspension (Fig. 2) is created by mixing the air foam with soil at a predetermined mixture ratio. Figure 3 shows the production procedure for air foam suspension.

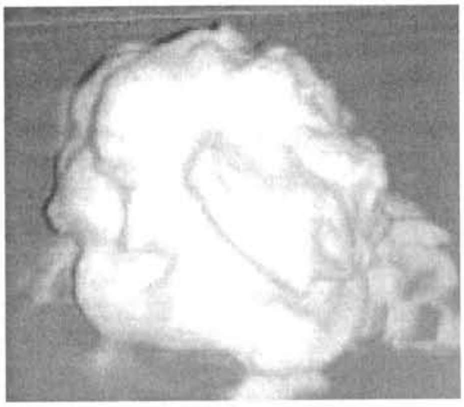

Figure 1. Air foam.

3 MANAGEMENT CHART FOR BENTONITE CLAY SLURRY

When bentonite clay slurry is used to stabilize the trench wall surface, the specific gravity and the funnel viscosity of the slurry are employed to control

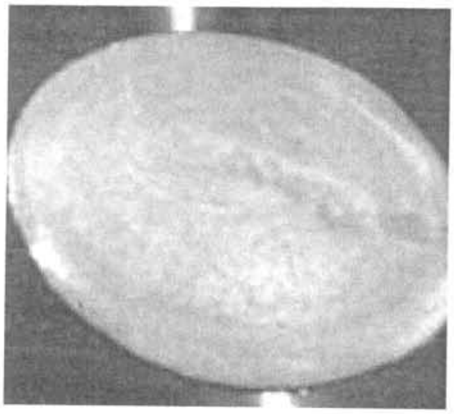

Figure 2. Air foam suspension.

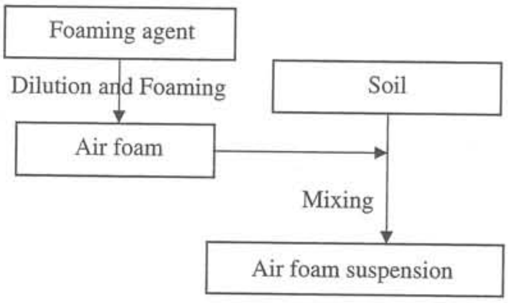

Figure 3. Production of air foam suspension.

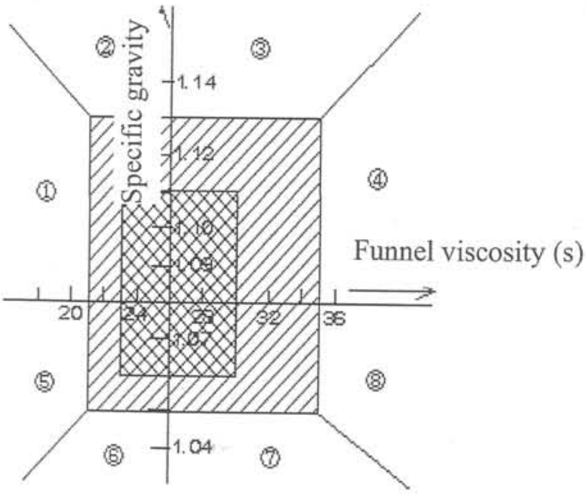

Figure 4. Management chart for bentonite clay slurry.

Table 1.1. Summary of bentonite clay slurry state and performance.

No	State	Performance
1	A lot of silt fractions exist in spite of low viscosity.	The mud film becomes thick and the amount of flow is large.
2	The separation of sand and clay takes place, and silt and sand mix.	There is an increase in precipitation slime.
3	Muddy water gels and silt and sand mix.	The replaceability of concrete and clay slurry is deficient.
4	There is an increase in specific gravity and viscosity.	Pump efficiency decreases. Poor reinforced concrete.
5	Viscosity is too low.	The mud film is thin and decay may occur. Large amount of drainage flow.
6,7	Bentonite volume is insufficient.	Weak mud film.
8	Excessive carboxy-methylated cellulose (CMC) which gels depending on the state of the cement.	pH is high. Poor reinforced concrete.

Table 1.2. Countermeasures to improve the performance of bentonite clay slurry.

No	Countermeasures
1	After the dispersing agent is added, replace it with CMC or bentonite.
2,3	Dispersing agent is added by circulation.
4	Dilution with water.
5	Addition of bentonite and CMC.
6,7	Addition of bentonite.
8	Neutralization of pH value.

the stabilization capacity, as shown in Fig. 4. In the lightly shaded area, the stabilization capacity is well established by the bentonite clay slurry, while the cross-shaded area indicates the region in which the trench wall is best stabilized by the slurry. In the regions outside the shaded areas with numbers, the bentonite clay slurry demonstrates poor performance.

Table 1.1 summarizes the slurry state and its performance (numbers correspond to those shown in Fig. 4); Table 1.2 indicates the countermeasures used to improve the performance of bentonite clay slurry. The performance of the bentonite clay slurry is easily judged from this Fig. 4, based on the measurement results of the specific gravity and the funnel viscosity.

4 MANAGEMENT CHART FOR AIR FOAM SUSPENSION

Systematic experimental investigations were conducted to obtain an appropriate management chart for the air foam suspension (Akagi *et al*. 2002):

(1) The unit weight of the air foam suspension was adopted, corresponding to specific gravity as a management indicator for the bentonite clay

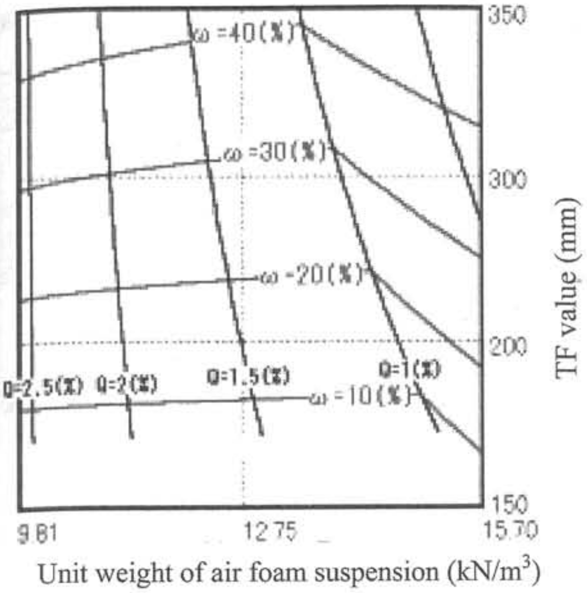

Figure 5. Relationships between unit weight and TF values of air foam suspension depending on Q and *w*.

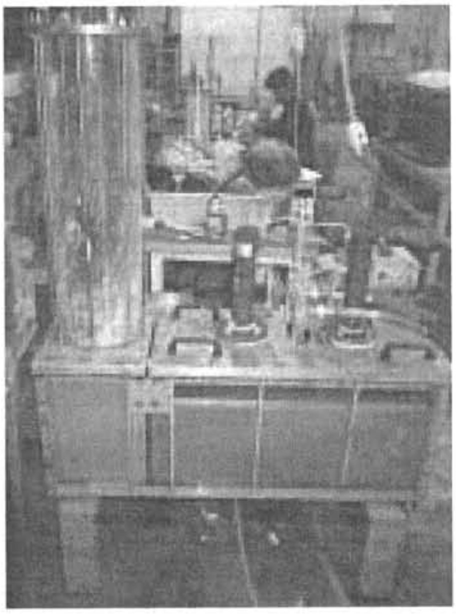

Figure 6. Model test apparatus.

slurry. The unit weight of the air foam suspension was obtained by placing the air foam suspension into a 1(l) measuring cylinder and weighing it. The table flow (TF) value of the air foam suspension was adopted for the factor, corresponding to funnel viscosity in bentonite clay slurry. The TF value was obtained by moulding the air foam suspension into a trapezoidal shape and rotating the steering wheel of the flow table. The maximum diameter of the air foam suspension on the table was measured after the rotation and was equal to TF value.

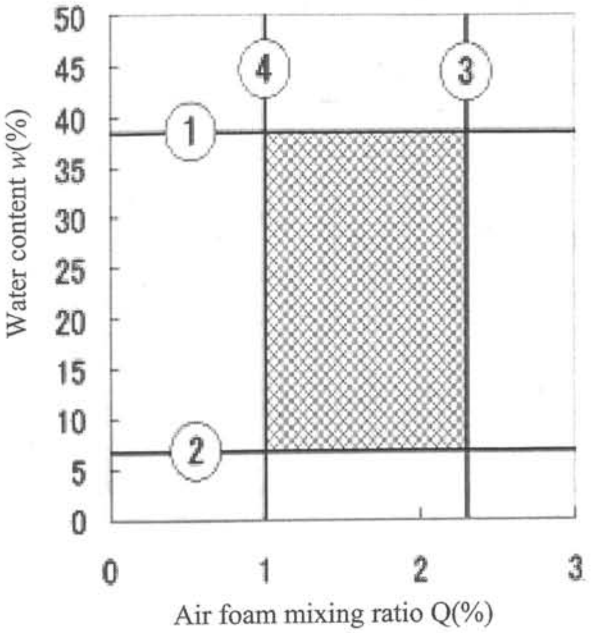

Figure 7. Range of water content and air foam mixing ratio for possible trench wall stabilization by air foam suspension.

Table 2. Poor performance of air foam suspension.

No.	Performance
1	The separation of soil particles from the trench wall.
2	Air foam suspension adsorbs the soil particles.
3	The pressure that acts on the trench wall is insufficient.
4	The amount of seepage water from air foam suspension increases rapidly.

The magnitude of TF value represents the viscosity of the air foam suspension. When the TF value is small, the Funnel viscosity of the suspension is high.

(2) The air foam mixing ratio Q and the water content of the air foam suspension *w* are key parameters, which control the air foam suspension performance. Many experiments were conducted to measure the unit volume weight and TF value of the air foam suspension; the experimental results are shown in Fig. 5. The relationships in this figure indicate the equivalent curves for Q and *w*.

(3) In order to obtain the trench wall stabilization capacity of the air foam suspension, a series of model tests were carried out employing the model test apparatus shown in Fig. 6, using Toyoura sand ($D_{50} = 0.1$ mm). The experiments showed that the stabilization of the sand trench wall using air foam suspension was achieved within the range of water content $6.7(\%) < w < 38.4(\%)$ and air foam mixing ratio $1(\%) < Q < 2.3(\%)$.

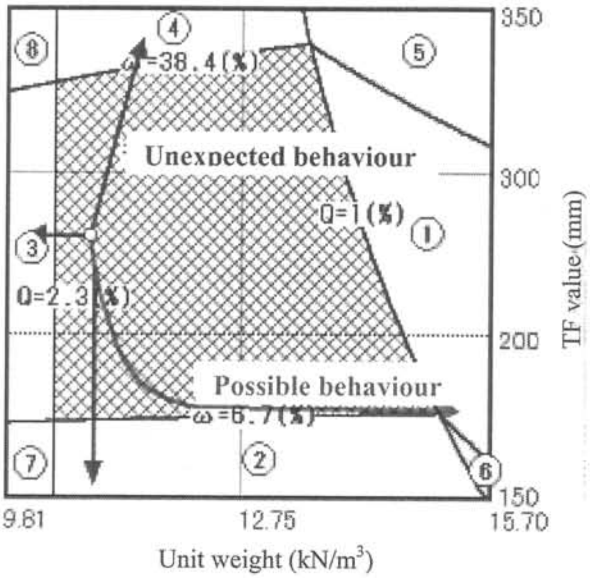

Figure 8. Management chart for air foam suspension.

The cross-shaded area in Fig. 7 shows the possible trench wall stabilization by air foam suspension. Fig. 7 shows the stabilization effects for air foam suspension, which correspond to those given for bentonite clay slurry in Fig. 4. Table 2 summarizes the poor performance of air foam suspension within the regions indicated by numbers in the figure. Using both Figs. 5 and 7, a management chart for air foam suspension is obtained as shown in Fig. 8.

The cross-shaded area in Fig. 8 indicates the region, in which the air foam suspension supports the sand trench wall successfully for 1 or 2 days by the end of concrete installation within the trench. In this figure, both the possible and the unexpected variations of the air foam suspension state during trench wall excavation are shown by the arrows. Possible behaviour indicates the settling of soil particles or the loss of air foam during the trench wall excavation. Unexpected behaviour is due to an increase in water content with a sudden rainfall. It is important to control the air foam suspension performance by the observation of its unit weight and TF value. Table 3.1 summarizes the poor performance of air foam suspension and its effects within in the regions indicated by numbers in Fig. 8; the countermeasures which may be used to improve the performance of the air foam suspension are presented in Table 3.2.

Table 3.1. Poor performance of air foam suspension and its effects.

No.	Performance	Effects
1	Separation of soil particles from the air foam suspension.	Possibility of trench wall collapse; difficult to replace with concrete.
2	Earth pressure acting on the trench wall is insufficient.	Possibility of trench wall failure.
3	The air foam suspension adsorbs the soil particles.	Loss of the consistency of the air foam suspension. Management becomes difficult.
4	The amount of seepage water from the air foam suspension increases.	Possibility of partial trench wall failure.
5	Combined performance of 1 and 2.	
6	Combined performance of 2 and 3 .	
7	Combined performance of 3 and 4.	
8	Combined performance of 4 and 1.	

Table 3.2. Countermeasures for air foam suspension.

No.	Causes	Countermeasure
1	The amount of the air foam is insufficient.	Addition of the amount of the air foam.
2	The water content is insufficient.	Addition of the water content.
3	The amount of the air foam is excessive.	Reduction of the air foam.
4	The water content is excessive.	Reduction of the water content.

5 DISCUSSION OF COST REDUCTION OF WALL EXCAVATION USING AIR FOAM SUSPENSION

In this chapter, a comparison of the cost necessary for the creation of a stabilizing liquid for wall excavation and the disposal of the excavated soil for trench excavation methods using bentonite clay slurry and air foam suspension is presented.

5.1 *Cost of stabilizing liquid*

The production conditions for the two types of stabilizing liquids are summarized in Table 4, while Table 5 shows their respective costs. The calculation procedure for the amount of air foam suspension is shown in Fig. 9. In the case of air foam suspension, the amount

Table 4. Production of stabilizing liquid.

Stabilizing liquid	Bentonite clay slurry	Air foam suspension
Dilution	5% bentonite concentration	20 times dilution
Air foam magnification	–	25 times
Mixing ratio (%)	50	100

Table 5. Cost of stabilizing liquid for 1(m^3) excavation.

Stabilizing liquid	Bentonite clay	Air foam
Amount (t)	0.0238	0.00008
Unit price (US$/t)	260	13,700
Cost (US$)	6	1

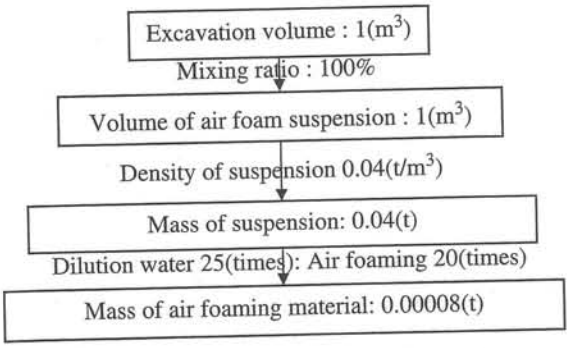

Figure 9. Calculation procedure for the amount of air foam suspension.

of surface-active agent is remarkably smaller than that necessary in the case of the bentonite clay slurry. Although the unit price of the surface-active agent is quite expensive, the resultant cost of air foam suspension is approximately one-sixth that of bentonite clay slurry.

5.2 *Disposal cost of excavated soil with stabilizing liquid*

Figure 10 shows the stages in the process of disposal of the excavated soil under the bentonite clay slurry method, which requires the disposal of the entire volume of the excavated soil. However, air foam within the stabilizing liquid is easily removed by drying followed by the addition of an anti-foaming agent, as shown in Fig. 11. If the full volume of the added air foam disappears completely by the addition of an anti-foaming agent, the excavated soil can be reused for other applications without any additional treatment.

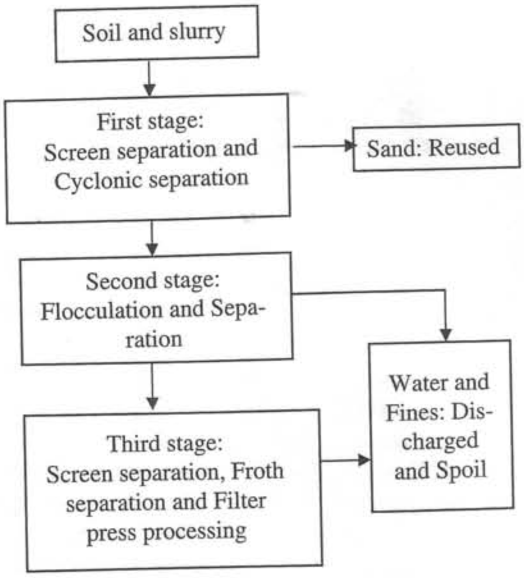

Figure 10. Disposal process of soil with bentonite clay slurry.

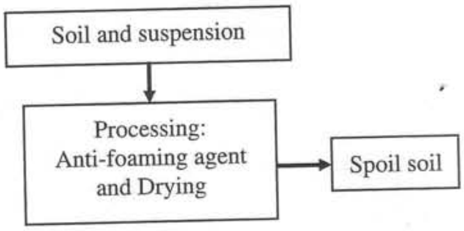

Figure 11. Disposal process of excavated soil and air foam suspension.

If the diaphragm wall excavation using bentonite clay slurry is carried out in sandy ground, the bentonite clay slurry is mixed by volume at approximately 50% of the excavated soil volume, as shown in Table 4. The total volume of the excavated soil with clay slurry is 1.5(m^3), though in fact, approximately 10% of the bentonite clay slurry volume is lost due to seepage through the mud film along the trench wall. The resultant volume of the soil with clay slurry is thus 1.45(m^3).

In the case of excavation with air foam suspension, the air foam suspension is mixed with the same volume of excavated soil, as indicated in Table 4. The total volume of the excavated soil with air foam suspension is 2(m^3); however in this case, approximately 20% of the air foam volume disappears during the mixing process. Consequently, the volume of the excavated soil with air foam suspension is 1.8(m^3).

It is possible to reduce the volume of the air foam suspension by using an anti-foaming chemical agent. Experimental investigation was conducted using a mixture of Toyoura sand and the air foam suspension with a silicon polymer-type anti-foaming agent.

Figure 12 shows the relationship between the anti-foaming agent ratio, i.e. the mass of anti-foaming agent versus the foaming agent mass, and the waste soil volume with air foam suspension. If the anti-foaming

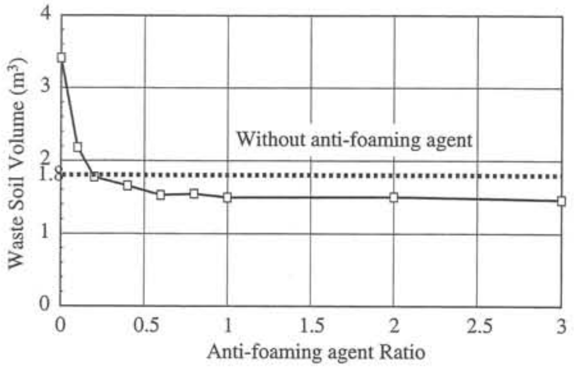

Figure 12. Relationship between anti-foaming agent ratio and waste soil volume.

agent ratio is less than 0.5, the waste soil volume becomes greater than its initial volume due to the additional formation of air foam with mixing. However, the amount of the waste soil volume is approximately 1.5(m^3) with an anti-foaming agent ratio of greater than 0.5, which is almost the same waste soil volume obtained in the case of bentonite clay slurry. Although the cost of an anti-foaming agent is almost the same as the foaming agent, the amount of anti-foaming agent is much smaller than the bentonite clay slurry, as shown in Table 5.

Therefore, the disposal cost of the waste soil with air foam suspension is approximately equal to that with bentonite clay slurry, since the resultant volume of waste soil with stabilizing liquid is almost identical in both cases.

The cost of diaphragm wall excavation using air foam suspension is thus equivalent to approximately 70% of that using bentonite clay slurry stabilization. It was consistent with the actual results obtained in a field test case of successful usage of the management chart, which produced a 30% reduction in the waste soil volume using the air foam suspension method.

6 CONCLUSIONS

In this paper, the development of a novel liquid, an air foam suspension, for stabilizing the trench wall surface during a diaphragm wall excavation was investigated. A management chart for the new air foam stabilizing liquid was presented, which was created through a series of experimental investigations. Finally, the costs necessary under the bentonite clay slurry method and the air foam suspension method for the creation of the stabilizing liquid for diaphragm wall excavation and for the disposal of the excavated soil are compared. The conclusions are summarized as follows:

(1) Quality management of air foam suspension can be conducted successfully using the unit weight and the TF value of the stabilizing liquid with air foam.
(2) Diaphragm wall excavation using air foam suspension can provide a reduction in cost of approximately 30% from the cost of stabilization and soil disposal with bentonite clay slurry.

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