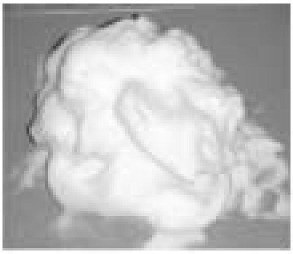
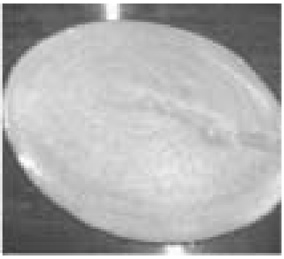
Cost reduction of diaphragm wall excavation using air foam and case record

Hirokazu Akagi, Waseda University, Tokyo, Japan
Yoshimasa Kondo, Magma Limited, Tokyo, Japan
Takashi Nakayama, Railway Technical Research Institute, Tokyo, Japan
Hisanaga Naoe, Japan Railway Construction, Transport and Technology Agency, Tokyo, Japan

Abstract
A novel stabilizing liquid using air foam rather than bentonite clay slurry, i.e. an air foam suspension method, was employed in order to stabilize the trench wall surface during a diaphragm wall excavation. This method reduces the construction costs of working on an underground diaphragm wall. An air foam suspension is created by mixing excavated soil with air foam made from a surfactant. The performance of the air foam suspension depends on its density and consistency, that is, its table flow value (TF). By comparing the trench stabilization capacity of an air foam suspension with that of bentonite clay slurry in model tests, the performance of air foam suspension was confirmed. A cost evaluation of the use of air foam suspension for diaphragm wall excavation is presented with an actual trial construction case record, which shows the superiority of air foam suspension to bentonite clay slurry as a stabilizing liquid.

Introduction
Currently, bentonite clay slurry is employed to stabilize trench wall surfaces during 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 trench wall surfaces during diaphragm wall excavation. 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 areas. The air foam suspension was produced from a surfactant by mixing the excavated soil with air foam in the mixing plant, from which it is then conveyed to the trench wall excavation.





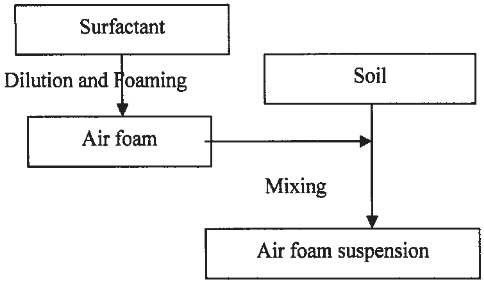


Figure 3. Production of air foam suspension.

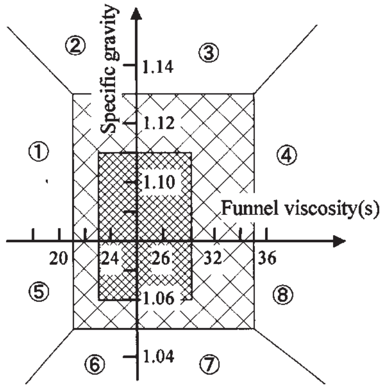


Figure 4. Management chart for bentonite clay slurry.

Air foam suspension

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

Management chart for bentonite clay slurry

When bentonite clay slurry is used to stabilize a trench wall surface, the specific gravity and the funnel viscosity of the slurry are employed to control 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 because of its filtration into the soil and the formation of a mud film along the trench wall surface. In the regions outside the shaded areas with numbers, the bentonite clay slurry demonstrates poor performance.

Table 1. Summary of bentonite clay slurry state, performance and countermeasures.

No	State	Performance	Countermeasures
1	A lot of silt fractions exist in spite of low viscosity.	The mud film becomes thick.	After the dispersing agent is added, replace it with CMC or bentonite.
2	The separation of sand and clay takes place, and silt and sand mix.	Increase in precipitation slime.	Dispersing agent is added by circulation.
3	Muddy water gels and silt and sand mix.	The replaceability of concrete and clay slurry is deficient.	Dispersing agent is added by circulation.
4	There is an increase in specific gravity and viscosity.	Pump efficiency decreases. Poor reinforced concrete.	Dilution with water.
5	Viscosity is too low.	The mud film is thin and decay may occur. Large amount of drainage flow.	Addition of bentonite and CMC.
6,7	Bentonite volume is insufficient.	Weak mud film.	Addition of bentonite.
8	Excessive carboxyl methyl cellulose (CMC), which gels depending on the state of the cement.	pH is high. Poor reinforced concrete.	Neutralization of pH value.

Table 1 summarizes the slurry state, its performance and the countermeasures used to improve the performance of the bentonite clay slurry (Numbers in the first column correspond to those shown in Fig. 4). The performance of the bentonite clay slurry is easily judged from Fig.4, based on the measurement results of the specific gravity and the funnel viscosity.

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, 2005):

1) A unit weight of the air foam suspension that corresponded to the specific gravity was adopted as a management indicator for the bentonite clay 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. A table flow (TF) value of the air foam suspension was adopted for the factor corresponding to the 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 the TF value. The magnitude of the 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 controlling air foam suspension performance. Many experiments were conducted to measure the unit volume weight and TF value of the air foam suspension; experimental results are shown in Fig. 5. The relationships in this figure indicate the equivalent curves for Q and w.

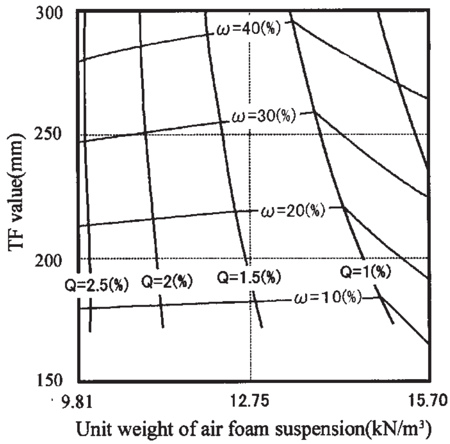


Figure 5. Relationships between unit weight and TF values of air foam suspension depending on Q and w.

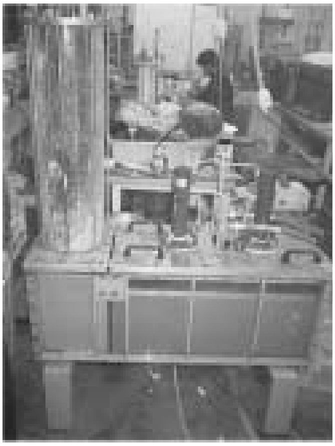


Figure 6. Model test apparatus.

3) In order to obtain 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}=0.1mm). The experiments showed that stabilization of the sand trench wall using the air foam suspension was achieved within the range of water content $6.7(\%) < w < 38.4(\%)$ with an air foam mixing ratio Q of $1(\%) < Q < 2.3(\%)$.

The cross-shaded area in Fig. 7 shows the possible trench wall stabilization by the air foam suspension because of its filtration into the soil and the formation of an unsaturated zone along the trench wall surface. Fig. 7 also shows the stabilization effects for the air foam suspension, which correspond to those given for bentonite clay slurry in Fig. 4. The numbers

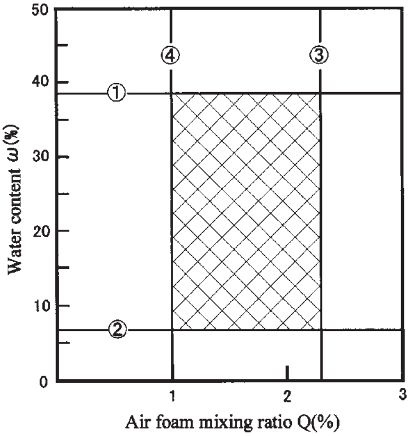


Figure 7. Range of water content and air foam mixing ratio for possible trench wall stabilization by air foam suspension.

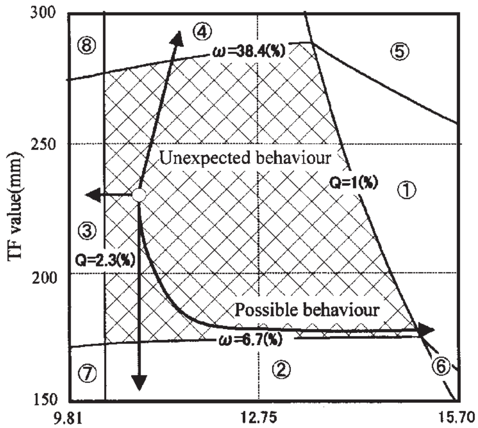


Figure 8. Management chart for air foam suspension.

within Fig. 7 indicate the areas of poor performance observed for the air foam suspension. In region No. 1, separation of soil particles from the trench wall was observed due to excessive water content. In region No. 2, soil particles were absorbed due to insufficient water content. In region No.3, the pressure acting on the trench wall was insufficient, when the air foam mixing ratio was too high. In region No.4, the water within the air foam suspension came out. 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 the steel reinforcement pile and the concrete installation within the trench. In this figure, both the possible and unexpected variations in the air foam suspension state during trench wall excavation are shown by arrows. Possible behaviour includes the settling of soil particles or the loss of air foam during the trench wall excavation. Unexpected behaviour is the result of an increase in water content

Table 2 Summary of air foam suspension performance, effect and countermeasures

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

from a sudden rainfall. It is important to control the air foam suspension performance by observation of its unit weight and TF value. Table 2 summarizes the poor performance of air foam suspension and its effects within the regions indicated by numbers in Fig. 8; the countermeasures which may be used to improve the performance of the air foam suspension are also presented in Table 2.

Discussion of cost reduction of wall excavation using air foam suspension

This section compares the costs 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, respectively.

Production Cost of stabilizing liquid

The production conditions for the two types of stabilizing liquids and their respective costs are summarized in Table 3. The calculation procedure for the amount of air foam suspension is shown in Fig. 9. In the case of air foam suspension, the amount of surfactant is remarkably smaller than that necessary in the case of the bentonite clay slurry. Although the unit price of the surfactant is quite expensive, the resultant cost of air foam suspension is approximately one-sixth that of bentonite clay slurry.

Table 3. Production and cost of stabilizing liquid for 1(m^3) excavation.

Stabilizing liquid	Bentonite clay slurry	Air foam suspension
Dilution	5% bentonite concentration	20 times dilution
Air foam magnification	—	25 times
Mixing ratio (%)	50	100
Amount (t)	0.0238	0.00008
Unit price (US$/t)	260	13,700
Cost (US$)	6	1

Disposal cost of excavated soil with stabilizing liquid

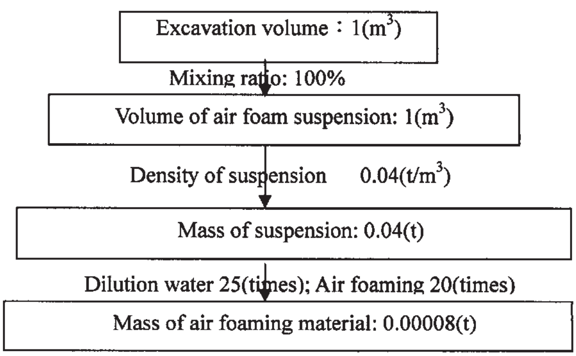


Figure 9. Calculation procedure for the amount of air foam suspension.

Fig. 10 shows the stages in the process of disposal of the excavated soil using 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.

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 3. 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 3. 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. The experimental investigation was conducted using a mixture of Toyoura sand and the air foam suspension with a silicon polymer-type anti-foaming agent. Fig. 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 the air foam suspension. When the anti-foaming agent ratio was less than 0.5, the waste soil volume became greater than its initial volume due to the additional formation of air foam with mixing. However, the amount of the waste soil volume was approximately 1.5(m^3) with an anti-foaming agent ratio greater than 0.5, which is almost the same waste soil volume obtained in the case of bentonite clay slurry. Although the cost of the anti-foaming agent is almost the same as that of the foaming agent, the amount of anti-foaming agent is much smaller than in the bentonite clay slurry, as shown in Table 3.

Therefore, the disposal cost of the waste soil with the air foam suspension is approximately equal to that with the bentonite clay slurry, since the resultant volume of waste

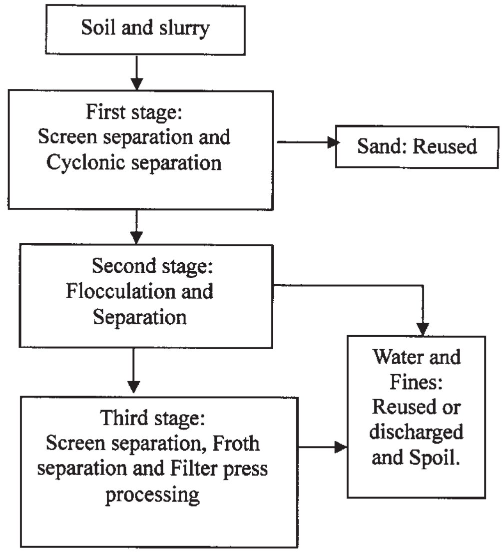


Figure 10. Disposal process of soil with bentonite clay slurry.

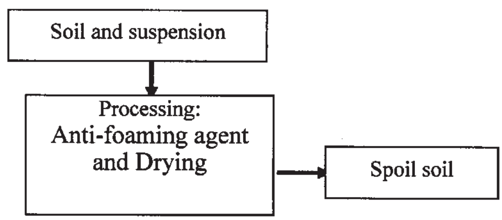


Figure 11. Disposal process of excavated soil and air foam suspension

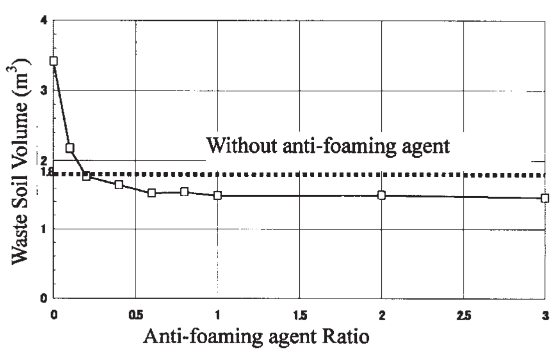


Figure 12. Relationship between anti-foaming agent ratio and waste soil volume.

soil with stabilizing liquid is almost identical in both cases. Consequently, the cost of diaphragm wall excavation using the air foam suspension is equivalent to approximately 70% of that using bentonite clay slurry stabilization. Since the chemical environmental compatibility of the air foam suspension is important, additional investigation is needed.

Case record of wall excavation using air foam suspension

The trial wall excavation using air foam suspension was conducted in the central part of Japan. The excavation depth was 9(m) and the length was 5(m). The thickness of the trench was 0.55(m). The soil profile consisted of silt with boulders. The trench excavation was performed with a chain saw type cutter called a TRD for Trench cutting Re-mixing Deep wall method. Figures 13(a) and (b) demonstrate the trench excavation and the installation of an H-shaped steel pile into the trench produced by TRD excavation using air foam suspension. The trench excavation was successfully completed with an air foam suspension. The H-shaped steel pile was more easily installed into this trench than into the bentonite clay slurry trench.
Table 4 compares the total amounts of spoil soil volume between the bentonite clay slurry excavation and the air foam suspension excavation. In the case of the bentonite clay slurry, the water versus content ratio (w/c) of the suspension within the trench needed to be increased for smooth installation of the H-pile. On the other hand, it was not necessary to increase the w/c ratio in the case of air foam suspension, since the fluidity of the air foam suspension is greater than that of bentonite clay slurry. Therefore, the amount of the spoil soil volume during

(a) (b)

Figure 13 Trial wall excavation using air foam suspension

Table 4 Comparison of spoil soil volume

	Excavation	Wall production	Total(m^3)
Bentonite clay slurry (m^3)	0.505	0.485 (w/c=150%)	0.990
Air foam suspension (m^3)	0.444	0.0606 (w/c=80%)	0.505

bentonite clay slurry wall production was around eight times of that of the air foam suspension. The total amount of spoil soil volume in the case of air foam suspension was around half of that in the case of bentonite clay slurry. Reduction of spoil soil volume by 50% led to a 50% reduction in the waste soil disposal cost.

Conclusions

In this paper, the development of a novel liquid, an air foam suspension, for stabilizing the trench wall surface during diaphragm wall excavation was investigated. A management chart for the new air foam stabilizing liquid is presented, incorporating the results of a series of experimental investigations. Finally, the costs necessary using the bentonite clay slurry method and air foam suspension method for the creation of a stabilizing liquid for diaphragm wall excavation and subsequent 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) Trail calculations show that diaphragm wall excavation using air foam suspension can provide a cost reduction of approximately 30% from the cost of stabilization and soil disposal with bentonite clay slurry.

3) A case record demonstrated that the trench excavation was successfully completed with air foam suspension and a 50% reduction of the waste soil disposal cost was achieved in the field using the air foam suspension.

Acknowledgements

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