

Golder Associates Ltd.

2180 Meadowvale Boulevard
Mississauga, Ontario, Canada L5N 5S3
Telephone (905) 567-4444
Fax (905) 567-6561



REPORT ON

**SITE VISIT DURING CONSTRUCTION
CUT-OFF WALLS AND DIAPHRAGM WALLS
HIGHWAY 416 PROJECT - CONTRACT 94-62
OTTAWA, ONTARIO**

Submitted to:

Ministry of Transportation, Ontario
Construction Office - Eastern Region
355 Counter Street
Kingston, Ontario
K7L 5A3

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1. INTRODUCTION

This note relates to a visit by Dr. Stephan Jefferis of Golder Associates (UK) Ltd. to the Highway 416 Project, Ottawa. The project involves two separate elements of slurry trench construction: a Portland cement-bentonite ground water cut-off wall and a structural diaphragm wall. Issues relating to the cut-off wall are discussed in Sections 1 to 6 of this note and brief conclusions on the cut-off wall are given in Section 7. Sections 8 to 12 discuss the structural diaphragm wall and Section 13 gives conclusions on this wall.

2. THE CEMENT-BENTONITE CUT-OFF WALL

2.1 The Slurry Mix Proportions

The cement-bentonite cut-off wall is a mix of Portland cement, bentonite, an additive with the trade name Aquafix and water. The mix formulation is as follows:

| | Per cent by weight of water | Concentration kg/m ³ of slurry | Relative density of material |
|-----------|--------------------------------|--|---------------------------------|
| Cement | 20 | 184.7 | 3.1 |
| Bentonite | 4 | 36.9 | 2.36 |
| Aquafix | 0.15 | 1.39 | 1.3 |
| Water | 100 | 923.5 | 1.0 |

The relative densities of the cement and bentonite have been taken from the letter EnviroTrench/Petrifond of 11 May 1995. This letter gives the relative density of Aquafix as 1.06 but notes it is 'to be verified at the lab'. However, the Material Safety Data Sheet for the material supplied to site shows a figure of 1.3. From the above mix proportions and material densities, the relative density of the slurry should be 1.147

The bentonite and cement concentrations are unexceptional for a Portland cement-bentonite slurry.

2.2 The Materials

2.2.1 The Bentonite

The bentonite used for the slurry is labelled 'pure Wyoming bentonite'. It is understood to be a bentonite which has not been polymer treated. Polymer treatment can improve the viscosity and fluid loss of a bentonite-water slurry which is likely to be beneficial for bentonite-water drilling fluids and diaphragm walling slurries. However, for cement-bentonite slurries the quantity of bentonite in the mix appears to be very important. Artificially viscosifying the bentonite therefore may not be beneficial as it can reduce the quantity of bentonite that can be incorporated in the slurry without it becoming unmanageably thick.

2.2.2 The Cement

This is understood to be a Portland cement. For equal strength and permeability in cement-bentonite materials pure Portland cement mixes require more cementitious material than cement-blastfurnace slag mixes. The extra cementitious material adds to the cost of the slurry but the has the advantage of reducing its sensitivity to drying. In theory it should also increase the cut-off durability to leaching by permeating water. However, experimental results to confirm this behaviour are not yet available in the literature.

2.2.3 Aquafix

Aquafix is a proprietary product supplied by Liquid Earth Support Inc. In the letter Envirotrench/Petrifond of 11 May 1995 Aquafix is described as a dispersant/retarder. The Material Safety Data Sheet for the product states it to be 'an aqueous solution of a neutralized homopolymer of acrylic acid'. The use of dispersants/retarders based on polymers, such as those derived from acrylic acid, is now quite usual practice - though the dose rate may have to be carefully adjusted to avoid excessive retardation (which will exacerbate bleed, see Section 3.4).

2.2.4 The Mix Water

Presumably mains water is being used. Contaminated mix water can inhibit the hydration of the bentonite and cause excessive bleed in both the bentonite and cement-bentonite slurries. Although, on site, bleed was seen in both the cut-off and diaphragm walling slurries it is not thought that the chemistry of the mix water is an issue. As a precaution it might be appropriate to obtain a typical analysis of the water from the supply company. Chemical species of most concern are magnesium, calcium, sodium and potassium. Electrical conductivity and pH also can be useful.

3. SLURRY CONSUMPTION

No data on the slurry consumption have been reviewed. Issues that will affect it are:

3.1 Trench Volume

The volume of the trench as dug including any overbreak.

3.2 Slurry Lost with the Excavation Spoil

There always will be some slurry lost with the spoil. This is largely outside the control of the contractor and depends on the degree of mixing of slurry into the spoil. However, some is also lost as bulk slurry if the excavator operator does not allow sufficient time for the free slurry to drain from the excavator bucket and also if the drain holes in the bucket are not of sufficient size or appropriately placed. Clearly there must be a balance between drainage time (which influences wall production rate) and slurry loss and one would not wish to encourage a claim for reduced production by seeking to save a modest quantity of slurry.

Whilst watching the excavation it seemed that more slurry was being lost than necessary (though no quantitative estimate was possible). It is believed that the excavator driver has a poor view of the draining bucket. Perhaps an 'oiler' could provide feedback.

3.3 Spoil Dispersion in the Slurry

Not only will the slurry mix with the spoil and be removed with it but also some spoil will disperse in the slurry and so remain in the trench. During excavation in silty soils the dispersion of spoil can be substantial. Fine non-cohesive soils generally disperse and remain in the slurry to the greatest extent. Some of the soils on site are slightly cohesive and thus dispersion may not be a major issue. The quantity of spoil in the slurry can be estimated from the final density of the slurry in the trench and density of the adjacent soil. For example a possible density for the slurry at the base of a trench could be 1350 kg/m³. For an initial slurry density of 1147 kg/m³ and a soil density of 1700 kg/m³ this density would correspond to a mix containing 37% soil by volume (63% slurry). Thus the final set material could contain over one third by volume dispersed spoil. Curiously this spoil usually appears to have little influence on the strength and permeability of the set material (when investigating test results, the position in the trench from which the sample was taken is often found to have no identifiable effect on these properties).

No data on the 'in-trench' slurry density have been provided. If the contractor does not supply these data (and it seems that he may not be doing any tests) then it will be difficult to select representative samples of the set slurry for laboratory testing to confirm its hardened properties. In this situation it may be necessary to test rather more samples than would have been necessary if density data were available. The samples for confirmation of set properties should cover the full length and depth of the trench.

3.4 Bleeding and Consolidation of the Slurry

A substantial quantity of water collects on the surface of the slurry overnight. This cannot be ground water as the slurry level starts above the ground water level. It may include some surface water, rain water, wash water, etc. (wash water was seen entering the diaphragm walling trench as the tremie pipes were removed and washed down).

Bleed water is the result of the slurry solids settling and the mix water being expelled. It may be regarded as a consolidation process. As consolidation progresses the

consolidation water drains to the upper surface of the slurry and also through the walls and base of the trench. The amount of bleed that collects on the surface of the trench will be influenced by:

- a) The permeability of the slurry to its own pore fluid
- b) The time necessary for the slurry to gain sufficient strength to prevent further settlement/consolidation of the solids, this will depend on the setting rate of the slurry and the effective stress
- c) The effective stress between the slurry particles. This will increase with depth in the trench
- d) The permeability of the surrounding ground. At some depths in the wall/locations on site it would seem that the ground is of relatively low permeability (compared with that of the stiffening slurry) as substantial quantities of bleed water are seen to collect at the surface

The interplay of these effects makes it very difficult to predict the amount of bleed water that will collect on the surface of the slurry in a trench, a priori.

It is understood that the slurry shows little or no bleed when tested in measuring cylinders of 250 ml capacity. In the UK the preferred size is 1000 ml as bleed is slightly sensitive to the test cylinder dimensions but the difference will be trivial. In the trench the bleed may be of order 1 m of water in a trench which may be about 15 m deep (i.e. 6.7%). This is relatively high but not wholly unusual. That no bleed is seen in the measuring cylinder test and yet of over 6% is seen in the trench is a demonstration that bleed is a consolidation process and sensitive to the effective stress, i.e. the depth of the trench. The measuring cylinder test therefore should be regarded as a test of the basic stability of the slurry and not a predictor of bleed in a trench. If high bleed is seen in a measuring cylinder test the slurry is unstable and should be rejected.

The level of the slurry appears to taper back from the point of excavation towards the previous day's working. This is as expected since the slurry remote from the excavator

will have consolidated to some extent during the working day. Thus at the end of the working day the slurry remote from the excavator will be partially consolidated and that immediately adjacent to the excavator unconsolidated. Clearly there will be some mixing along the trench and thus the variation in degree of consolidation with position in the trench will be somewhat blurred. At the end of a day's work the slurry level in the trench will be approximately horizontal as during the day fresh slurry will have continually flowed back along the trench to replace the loss due to consolidation. However, consolidation will continue after work stops and it follows that the slurry nearest the excavator will have the greatest potential for further consolidation. The stiffening of the slurry will stop it from flowing to maintain itself level. Thus the tapering shape will develop with a gently increasing depth of bleed water towards the most recently excavated part of the trench. In passing it may be noted that if the bleed is very rapid, more rapid than the slurry stiffening, then some slumping of the slurry in the trench will occur.

The Aquafix is likely to increase the consolidation of the slurry as it will not only make it more fluid but also it is likely to act as a retarder of set. The contractor appears to believe that the Aquafix is essential to the performance of the slurry. If the need for it is to be questioned it would have to be investigated by rheological testing of the treated mix and an untreated control. However, as the rheology of a mix will depend on the mixer used, obtaining an appropriately mixed control would require preparation of a special trial batch in the site mixing plant.

3.5 Overall Consumption

Although bleed is a very obvious manifestation of slurry loss it is generally not the major issue relating to slurry usage which is overbreak during excavation and the balance between the slurry lost with the excavation spoil and the increase in volume as a result of spoil dispersion in the slurry. Typically, in the UK, slurry consumption may be perhaps 15 to 40% greater than the theoretical volume of the trench. The contractor has suggested a figure of 50% for the Portland cement slurry which is being used. This seems rather high and should not be accepted without justification.

The actual quantity of slurry produced is likely to be recorded on counters on the batching plant. It can also be calculated from the materials delivery notes. If the cumulative cement, bentonite and Aquafix consumption are plotted against the cumulative volume of wall completed it should be possible to get a reasonable estimate of the excess slurry used over the theoretical quantity. It should also be possible to check that the materials are being used in the design proportions. It will be much more difficult to assess how the slurry loss so calculated might compare with that for a slag-bentonite mix.

4. CEMENT-BENTONITE SLURRY PREPARATION

The cement-bentonite slurry preparation involves two stages: the mixing of bentonite and water to produce a bentonite-water slurry followed by the addition of cement to produce the cement-bentonite-water slurry.

4.1 Bentonite Water Mixing

The stages in the bentonite slurry mixing are understood to be as follows:

- a) Mixing of water and bentonite in a large mixer (capacity several cubic metres). The mixer was not examined in detail but seemed typical of those used for bentonite-water mixing.
- b) The bentonite-water slurry is pumped from the mixer to a storage pond. During my visit there was evidence of settlement of the partially mixed bentonite solids and formation of 'pockets' of bleed water. This was occurring despite the recirculation of the slurry through a pump mounted at the side of the pond. Unfortunately, although producing a substantial flow this pump was only mixing

an area of the pond immediately adjacent to it. The flow from the pump should be returned to the pond via a number of jets distributed around the pond.

- c) From the storage pond the slurry is pumped to a second pond from which it is drawn off for use. The purpose of the two pond system is to ensure that the slurry is hydrated for at least a minimum specified time before addition of the cement, which effectively stops further dispersion of the bentonite. The use of a two stage pond or multiple tank system is normal practice in the UK.

It should be noted that heavy rain could have some effect on the bentonite slurry concentration in the ponds. The significance of any effect will depend on the level of the slurry in the ponds at the time of the rainfall. It is impracticable to cover the ponds and difficult to make allowance by increasing the mix concentration as the amount of any rainfall cannot be known in advance.

4.2 Cement-Bentonite Slurry Preparation

From the second pond the slurry is pumped to a mixing station where the cement is added. This part of the plant was not inspected as it was within the contractor's fenced compound. However, from an external perspective it seemed typical of the type of plant used for cement-bentonite slurry production.

From the cement-bentonite mixing plant the slurry is pumped to a storage silo and thence to the trench.

5. SLURRY TESTING

From the slurry record sheets it would seem that the contractor is measuring the density, Marsh funnel viscosity and pH (with paper strips) of the bentonite-water slurry and the fresh cement-bentonite slurry. Data for the period 11 September to 19 September 1995 were provided to me. These show:

| | Bentonite slurry (12 test results) | Cement-bentonite slurry (11 test results) |
|----------------------------------|---------------------------------------|--|
| Relative Density | | |
| Maximum | 1.02 | 1.15 |
| Minimum | 1.02 | 1.14 |
| Average | 1.02 | 1.15 |
| pH | | |
| Maximum | 10 | 12.5 |
| Minimum | 9 | 12 |
| Average | 9.5 | 12.4 |
| Marsh Funnel Viscosity (seconds) | | |
| Maximum | 31 | 60 |
| Minimum | 29 | 39 |
| Average | 29.5 | 46.9 |

5.1 Relative Density

For the bentonite-water slurry the relative density is consistent at 1.02. For the cement-bentonite slurry it is in the range 1.14 to 1.15. The theoretical values are 1.023 and 1.146 respectively for the two slurries. Thus, at first sight, it would appear that the slurries are being correctly batched. However, it is necessary to consider the resolution of the density measuring equipment - a mud balance. The smallest scale division on this instrument is 0.01 and at best it is repeatable to ± 0.005 . For a bentonite slurry the range 1.018 to 1.028 (i.e. ± 0.005 from the mean of 1.023) corresponds to a range of bentonite contents of 3.1 to 4.9%. Similarly for a cement-bentonite slurry containing 4% bentonite a density range of ± 0.005 about a mean of 1.146 corresponds to a range of cement contents of 19.1 to 20.9%. Thus on the basis of the density tests the detectable error in bentonite batching will be a concentration error of $\pm 0.9\%$ or $\pm 22\%$ of the nominal batch weight. For the cement the detectable error will be $\pm 4\%$ of the nominal batch quantity. The possible error in bentonite batching is quite unacceptable. In contrast the cement value is acceptable provided that the mud balance is kept in excellent condition and regularly checked with water to confirm that it is correctly set.

Because of the poor resolution of the mud balance for slurry control it is suggested that:

- a) The weights of materials delivered to site are checked against the volume of slurry batched to confirm the overall mix proportions
- b) The bentonite content of the bentonite water slurry should continue regularly to be checked by oven drying. It is understood that to date results of the drying show a bentonite content of 3.2 to 3.3%, for the slurry at the outlet pump of the second bentonite pond, rather than the design figure of 4% and that laboratory tests have shown that some of the discrepancy can be accounted for by settlement of sand from the bentonite. Any greater discrepancy must be investigated. Oven drying of the cement-bentonite shows a solids content of 26.2 to 27.4% by weight of water evaporated. This is rather higher than the theoretical value which would be around 23.5% if all the water in the hydrates produced by the reaction of cement and water were evaporable at the oven temperature of 105°C. For fully hydrated cement in concrete of the order of 23% water by weight of cement is combined in the hydrates and is not evaporable at 105°C. If 23% water by weight of cement in the cement-bentonite mix were non-evaporable then the solids content would be of order 29.5%. However, for a young slurry probably less than a day old at the time of drying, it is unlikely that as much as 23% would be non-evaporable. The measured range of 26.2 to 27.4% therefore seems reasonable as regards the absolute numbers and the narrowness of the range.

5.2 pH

The pH is being measured with pH papers. The papers are readable to about +/-0.5 pH units. Thus the observed range (9 to 10 for the bentonite slurry and 12 to 12.5 for the cement-bentonite slurry) probably has more to do with the readability of the papers than any variation in the true pH of the slurries.

However, it should be noted that a range of pH of 9 to 10 could be significant for the bentonite slurry, if it is actually occurring. Although not of high priority it would be useful to measure the pH of some of the samples taken for moisture content determination (see Section 5.1(b)) with a pH electrode prior to drying to confirm that the pH is reasonably consistent.

The range of pH for the cement-bentonite slurry is 12 to 12.5. Even a small amount of cement will raise the pH of a bentonite slurry to over 12. Thus it would be very surprising and indicative of a gross batching error if the pH of a cement-bentonite slurry were less than 12. Although the pH range as indicated by the papers is 12 to 12.5 the actual pH, if measured with an electrode, is very possibly higher. That is the papers may be showing a systematic error. Fundamentally a pH of the cement-bentonite slurry is of minimal use for control purposes as it would detect only an extreme under dosing of cement.

5.3 Marsh Funnel Viscosity

The range of Marsh funnel viscosity for the bentonite slurry is 29 to 31 seconds. This is a narrow range but it should be remembered that the flow time for water is 26 seconds (for a discharge of 946 ml) and for times close to 26 seconds the discrimination of the instrument is limited.

The range for the cement-bentonite slurry is 39 to 60 seconds which is much wider. However, such a range easily can be accounted for by:

- a) Testing samples which have been allowed to age for some time after mixing
- b) Testing samples with differing shear histories e.g. direct from the mixer, from the storage tank or from the end of the pipeline to the trench
- c) The age of the bentonite at the time of the cement-bentonite slurry preparation. A bentonite slurry allowed to hydrate over a weekend could give a markedly higher viscosity cement-bentonite mix than an overnight hydrated slurry

Whilst the above can all influence the Marsh funnel time it should be noted that variations caused by (a) and (b) will have no effect on the properties to the set slurry in the trench and (c) will have only a quite modest effect - if any is detectable.

5.4 Control of the Slurry

From the comments in Sections 5.1 to 5.3 it is clear that the mud balance, Marsh funnel and pH papers are scarcely appropriate as quality control tests on bentonite and cement-bentonite slurries. Checking and control of batching accuracy and mixing times is the best procedure.

6. THE EXCAVATION PROCESS

6.1 The Backhoe

The backhoe is stated as being capable of excavation to a depth of 65 ft (19.8 m). At the present time the maximum reach with a backhoe in the UK is about 52.5 ft (16 m). The backhoe thus has markedly greater reach than any plant currently available in the UK. Very often in the UK there are problems in that long reach backhoes have insufficient power when working at depth. However, the Taggart backhoe has rather the reverse problem. The power is such that when toeing into the rock teeth have been lost and there has been damage to connecting pins etc. UK experience cannot provide much help on the excavator performance and if damage to the teeth etc. is likely to be an issue then it may be appropriate to seek local advice.

At the scale that the backhoe is working it must be difficult to achieve fine tolerances in the excavation, for instance the amount of cut-back into the previous day's working at the start of a new day. It was not possible to be present at the start of a working day and thus the slurry wastage at this time was not observed. However, from the relatively slow setting of the mix it is likely that the mix should be easily re-worked/re-fluidised each morning so that little solid slurry would be removed. This could be confirmed by observation of the start up on a few mornings.

6.2 The Clamshell Excavator

The excavation with the Casagrande hydraulic clamshell grab seemed quite reasonable, though there was considerable drop in the slurry level as the grab was removed from the trench. There also appeared to be some wastage of slurry as the grab was hoisted rather high above the trench when the slurry was draining from it. The surrounding ground was covered with the draining slurry and there was some washing of the surface soil around the rim of the trench into the trench.

6.3 Bleed Water

For both the Casagrande rig and the backhoe the pumping of the water from the trench prior to the start of excavation each morning caused some slumping of slurry from the adjacent parts of the trench. This may cause some cracks to develop in the slurry. If severe slumping occurs it may be necessary to remix the slurry in the area where slumping has occurred after the water has been pumped off and the trench re-filled with the slurry.

If the bleed increases above the present level it could be necessary to resort to topping up slurry during the overnight period. However, this would be difficult and expensive.

7. CONCLUSIONS REGARDING THE CEMENT-BENTONITE CUT-OFF WALL

Overall the cement-bentonite wall is typical of many that I have seen save that the quantity of water accumulating at the surface of the slurry overnight is rather higher. As already discussed this may be due to the combination of a number of factors including the depth of the trench and the permeability of the surrounding ground. The Aquafix also may be delaying the set. If bleed water is an issue with the contractor it may be necessary to investigate the effect of the dose rate of Aquafix on the strength development of the slurry.

The practice of checking the bentonite content of the bentonite-water slurry and the overall solids content of the cement-bentonite slurry by oven drying is important and should be continued. The mix proportions and especially the bentonite content must be kept at the design figures and any discrepancies investigated.

As the cement-bentonite slurry is showing some bleed and high bleed can be correlated with short hydration times the bentonite hydration time should be rigorously policed. There should be no relaxation of the 4 hour minimum currently permitted - at least not without demonstration that there is no adverse affect on the bleed.

8. THE STRUCTURAL DIAPHRAGM WALL

8.1 Introduction

The principal issues relating to the structural diaphragm wall are:

- a) The quality of the excavation slurry
- b) The overbreak manifested in high concrete takes
- c) The location of the overbreak
- d) Displacement of the slurry around the reinforcing bars and anchor box-outs
- e) Lifting of the cages during concreting

9. THE SLURRY

I have examined data for the slurry for the period 12 July to 12 September. It would seem that the range of values for the fresh slurry from the storage pond were as follows:

| | Minimum | Maximum |
|--|---------|---------|
| Relative density | 1.02 | 1.05 |
| pH | 8 | 9 |
| Viscosity (seconds) | 32 | 44 |
| Gel strength, Pa | 2.86 | 5.75 |
| Filtrate loss, ml in 30 minutes at 100 psi | 17 | 25 |

With the exception of the relative density values the results are all quite reasonable and the variation is no greater than might be expected on samples taken from a pond containing slurry of a variable hydration age. Perhaps the most important figure is the fluid loss. The relatively low figures, 17 to 25, show that the bentonite (and any additives it contains - it is understood to be a different bentonite to that used for the cut-off wall and to include a polymer) is behaving satisfactorily.

The relative density values are odd. A density range of 1.02 to 1.05 for a fresh bentonite slurry corresponds to a range of bentonite contents of 3.5 to 9% which seems improbable. It would therefore seem that either:

- a) The density test is not being undertaken with sufficient care
- b) The test is occasionally being carried out on a sample from the bottom of the pond containing some sediment - though there should be no sediment
- c) The mud balance calibration is changing

Fundamentally it must be concluded that either the mud balance and/or the test procedure is unsatisfactory or the bentonite solids are settling. This does not bode well for the use of the mud balance as a quality control test for the cut-off wall slurry where the effect of any errors in batching could be very significant.

The test results for the slurries from the trench, at 0.3 m above the base of the panels, for the period, 12 July to 12 September, show rather higher densities, as would be expected, and comparable fluid losses. Thus it would seem that the slurry in the trench was acceptable slurry (though note I have minimal data on viscosity and shear strength of the slurries - these parameters do not seem to have been recorded). Also as shown in Appendix 1 there is considerable concern that the slurry will begin to enter and may indeed fill the sampler at quite shallow depths and thus the samples will not have come from 0.3 m above the base of the trench.

9.1 Slurry Cleaning

After use in the excavation the slurry is cleaned using a large hydrocyclone. A bank of smaller hydrocyclones is also available to further clean the slurry in the pond. It would seem that the slurry is pumped direct from the trench to the large hydrocyclone and that it is not screened prior to this hydrocyclone. It is therefore important that the slurry does not contain any oversize material which could block the underflow nozzle of the hydrocyclone. This is achieved by having relatively fine openings in the strainer at the trench end of the suction pipe used to recover the slurry during concreting. This strainer appears to block regularly and when I was watching and the resulting slow rate of removal of the slurry was impacting on the rate of concreting - an unsatisfactory situation.

9.2 Chemical Treatment

It would seem, from the materials noted on site, that Petrifond has available three additives for treating the slurry:

sodium tri-polyphosphate

sodium carbonate

sodium carboxymethyl cellulose

Sodium tri-polyphosphate is a thinner and is often used to thin slurries especially if contaminated with spoil or concrete.

Cement contamination can cause ion exchange of the bentonite (calcium for sodium). This can be reversed with sodium carbonate which will convert calcium bentonite to the sodium form. However, sodium carbonate addition tends to cause some thickening of the slurry. It is therefore more usual to use sodium bicarbonate which has a lower pH and is more effective in controlling the thickening caused by cement contamination.

Sodium carboxymethyl cellulose (cmc) is a viscosifier and fluid loss control agent. It is understood that Petrifond occasionally add cmc to the slurry, as a powder at the surface of the trench, at a rate of perhaps 5 to 15 kg per panel. The volume of the panel may be of order 40 m³ and thus the addition rate will be of order 0.012 to 0.036%. This is a relatively low addition rate. Typical addition rates in the oil industry for treating clay based drilling fluids are in the range 0.25 to 1%. The addition of cmc direct to the slurry can lead to lumping and poor dispersion with some cmcs. However, a simple trial with some of the material on site suggests that it is a grade which does not lump. However, addition at the surface will not give good dispersion throughout the depth and also it may be preferentially sorbed on the bentonite clay it first contacts, thus diminishing its overall effect.

Overall, Petrifond are perhaps not making the optimum use of the additives on site. In the UK the use of additives for slurry treatment is now very much at the contractor's discretion and thus not the province of the client/consultant unless there is the potential for damage to the permanent works or there are cost issues.

Optimum use or otherwise it must be noted that the slurry properties recorded on the record sheets are unexceptional. In particular the viscosity and fluid loss are well within typical specification limits. When comparing specifications for pH it is important to keep in mind that calcium bentonites that have been converted to the sodium form with sodium carbonate (i.e. most bentonites of UK and European origin) can have markedly higher pH than natural sodium bentonites such as Wyoming bentonite.

10. OVERBREAK

From discussions on site it would seem that there is an impression that:

- a) The overbreak is occurring in the deeper parts of the trench rather than the shallow
- b) The overbreak may be occurring prior to the churn drilling as rather modest quantities of spoil are removed after the churn drilling

- c) The overbreak is greater on the east wall where there is little glacial till or sand and most of the excavation is in clay. However, it should be noted that the east wall is deeper than the west wall and trench stability theories generally predict a decreasing stability with depth

It is also clear that the overbreak is often much higher in the opening panels than the running panels and perhaps lowest in the closing panels. In part this is to do with the method of calculating the overbreak as discussed in Section 11.2.

10.1 Stability of the Trench

The stability of any element of the trench will be a function of difference between the local pore pressure in the soil and the hydrostatic pressure of the slurry.

In sands and gravels any water lost from the slurry may be rapidly dissipated with little increase in pore pressure in the adjacent soil. This water loss will lead to the formation of a filter cake which will tend to bind the surface of the soil and help to stabilise it. In a clay there will be no significant water loss. In some silts and fine sands there may be sufficient fluid loss to markedly raise the pore pressure but not sufficient to build a tight cake (the cake formed from a bentonite slurry may have a hydraulic resistance comparable to about 1 m of 10^{-9} m/s soil).

The overall effect is that silty materials may not be well stabilised. If no cake forms not only will stability be reduced because of pore pressure increase in the surrounding ground but also because of lack of a binding cake at the ground/slurry interface.

In the section of wall exposed by excavation during my visit there was a sharp overbreak at about 3 m from the surface. From inspection of the soil profile it seems that this may have coincided with a layer of coarser sand/silt in the clay. The shape of the overbreak suggested that this layer formed a parting surface and that a block of clay had fallen out.

However, it should be noted that the adjacent panel did not show such a flat surface. Perhaps because the fissures in the clay are undulating.

Other issues that could affect the stability of the trench are the dynamic loading during chiseling and the chisel falling sideways after impact on the base of the trench (an imprint of the shaft of the drill was seen on one exposed panel). If the overbreak is as a result of churn drilling then either additional spoil should be found in the base of the trench after drilling or the density of the slurry should increase during drilling - and more likely the latter as any overbreak arising from churn drilling could be rapidly worked into the slurry by the action of the chisel. As an example of the effect of spoil on the density of a slurry it would take 42% by volume of a spoil of density 1700 kg/m^3 to raise the density of a slurry from an initial value of 1100 kg/m^3 to 1350 kg/m^3 , a reasonable value at the end of excavation. Although such an increase in density might be limited to a region near the base of the trench it is clear that a density increase could mask the spoil arising from a significant amount of overbreak.

To date there does not seem to be any particular evidence for an increase in slurry density during churn drilling but equally it does not seem to have been investigated in any detail. Also there is concern about the performance of the sampler (see Appendix 1). It is suggested that a programme of investigation of the density of the slurry before and after drilling should be undertaken as well as a more careful estimate of the amount of spoil removed at the end of drilling.

10.2 Ground Water Level

A fundamental issue for trench stability is the relative positions of the ground water level and the slurry level. Petrifond have suggested that for a slurry of density 1.1 g/ml in a 13 m deep trench a reduction in the slurry head above the ground water from 1.5 m to 1.0 m would reduce the factor of safety from 1.22 to 1.19 i.e. by only 3% (Letter Petrifond/Taggart of 31 July 1995). They have not presented sample calculations to justify this assertion. Golder have now undertaken stability calculations and the effect of ground water level can be reviewed.

The contractor should be required to keep the slurry level in the trench as high as practicable. In places this is limited by variations in the level of the working platform and drainage of the slurry to low points. It may be necessary to dam the trench at intervals so as to maintain as high level as possible at the point of excavation.

Raising the guide walls so as to increase the slurry pressure would undoubtedly increase the stability of the trench and could be considered - especially as dewatering cannot be countenanced - except perhaps within the excavation - and this is the area where overbreak will be of the most significance as it must be broken off to enable the cladding to be installed. However, raising the guide walls is unlikely to prevent all overbreak and thus a contractor could query the balance between the cost of raising the walls and the benefit achieved.

In the UK the Federation of Piling Specialists Specification for cast in place concrete diaphragm walling (1973) requires that: 'During construction the level of bentonite slurry in the trench shall be maintained within the depth of the guide walls, and at a level not less than 1.0 m above the level of the external standing ground water'. The specification also includes a note for guidance which states that: 'the top of the guide wall should, preferably, be not less than 1.5 m above any standing ground water level, and the guide walls must be capable of being constructed in the dry'. The specification dates from

1973 and the requirement for a minimum of 1 m excess of slurry level over ground water level is well established practice.

11. ANALYSIS OF THE OVERBREAK

11.1 Position of the Overbreak in the Excavation

Petrifond have provided reports on the concreting of some of the panels (Rapport de Betonage). These reports provide a record of the depth of the concrete in the panel as a function of the volume of concrete placed. Petrifond calculate the overbreak on the basis the theoretical volume of concrete required to fill the trench. Table 1 summarises the numerical data which have been extracted from the concreting reports which I have reviewed. Figures 1 and 2 present the data from the reports in graphical form. In these figures the overbreak has been plotted against the average depth of concrete in the trench (measured from the top of the guide wall) and also against the average height in the trench measured from the base of the trench. This latter graph has been prepared specifically to investigate the possibility that the overbreak is related to the churn drilling and in particular damage inflicted on the walls of the trench by the drill falling sideways after impact on the base of the trench or general disturbance of the soil near the toe of the trench during drilling.

From Figure 1 it can be seen that for many of the panels the overbreak is relatively insensitive to the depth in the trench, though for some panels there is an increasing trend up to a depth of about 5.5 m and a reduction thereafter, others show a slight increase for all depths. Figure 1 also shows that the overbreak is not always uniformly distributed and that for a few panels the local overbreak can be much greater than the average overbreak. In Figure two panels show particularly high local overbreak, W52 and E4. It is understood that for W52 there was an old sewer line and the upper part of the panel was excavated in loose fill. For E4 the local overbreak peaked at 228% which may be compared with an average overbreak of 76% for this panel. The high overbreaks do not seem to occur at a consistent depth - high values are seen at depths of <2 m, around 5.5 m and >7 m.

The same data are presented in Figure 2 but as overbreak as a function of height from the base of the trench. The figure shows that there is no obvious correlation with this height. A number of panels show high overbreaks at 2 to 6 m from the base of the trench. At around 6 m this could be due to the churn drill falling sideways after impact. However, there is only one panel that shows a markedly higher overbreak at this depth.

It should be noted that once the concrete has reached the level of the toe of the guide walls (1 m) the overbreak should be no more than about 5% (the guide walls will be slightly wider apart than the nominal width of the trench). Not all the panels have data relating to concrete depths within the guide walls. However, it can be seen that where there are data the overbreak is not always at the <5% level. This suggests that there may be inaccuracies in the depth measurement (or the concrete volume measurement) or that concrete does not flow into all the lower overbreak voids until it is slightly pressurised by the placement of further concrete.

11.2 Overbreak as a Function of Panel Type

The data in Figures 1 and 2 has been divided into 3 groups. Data for Opening panels (shown as full lines), for Running panels (shown as dotted lines) and Closing panels (dashed lines).

From Figure 1 and 2 it is not clear that there is any significant difference in the overbreak between the Opening and Running panels. This is confirmed by the average overbreak figures at the foot of Table 1 where it is shown that the ratio of average overbreak in Opening to Running panels for the data set of Figures 1 and 2 (given in Table 1) is 1.01. However, the Closing panels generally show markedly lower overbreak as can be seen in Figures 1 and 2 and from the ratio of overbreak for Closing to Running panels in Table 1 which is 0.62.

However, before considering overbreak in detail it is necessary to consider the way in which the overbreak is calculated and reported. For any panel the volume to be concreted

and the volume excavated are not necessarily equal. For example for Opening panels the nominal length is 5 m plus the space for two 0.75 m diameter stop ends. Hence the overall excavated length is 6.5 m but during concreting the stop-ends will be in place and thus the length to be concreted will be 5 m. Overbreak will occur during excavation and create a continuous void. During concreting the entire void will be filled with concrete except the for the volume occupied by the stop ends. In contrast, for the Running panels, at the start of excavation there will be a 0.75 m void left by the stop end from the previous panel and a 5 m excavation will be undertaken to give a total open trench length of 5.75 m. During concreting there will be a stop end in place at the leading end of the panel and thus the concreted length (5 m) will be equal to the excavated length for the panel. For the closing panels the concreted length will be greater than the excavated length. The situation for the three panel types may be summarised as follows:

| | Excavated length | Maximum open length | Concreted length |
|----------------|-------------------------|----------------------------|-------------------------|
| Opening panels | 6.5 | 6.5 | 5 |
| Running panels | 5 | 5.75 | 5 |
| Closing panels | 3.5 | 5 | 5 |

NB: These are nominal figures. There appears to be some variation in the actual length of panels.

The importance of the difference between the maximum open length and the excavated length is that although at the end of excavation all panels may be of comparable length the amount of unconcreted overbreak will be different. All overbreak within the maximum excavated length will be filled during concreting except that which was filled whilst adjacent panels were concreted. Thus it is the overbreak within the excavated length that will be concreted with a panel. It follows that for the proper investigation of overbreak it should be considered per unit length of excavation and not per unit length of concreted wall. Thus using the above lengths Petrifond's Opening panel overbreaks should be divided by a factor of 1.3 (5/6.5). The overbreak on the Running panels need not be factored as the excavated and concreted lengths are equal (the purist will note that

these lengths overlap but are not coincident). The overbreak in the Closing panels should be divided by a factor of 0.7 to put the data on the common basis of overbreak per unit length of excavation.

Figures 3 and 4 show the data from Figures 1 and 2 replotted in this way. It can be seen that the distinction between the three panels is less apparent.

Table 2 gives overbreak for another set of panels. The data have been taken from the Diaphragm Wall Construction (South Side) Record Sheets and now show markedly higher overbreaks for the Opening panels than the Running panels (the data set does not include any Closing panels). The average overbreak of the Opening panels being 2.5 times that of the Running panels by length concreted and thus just under twice that by length excavated (i.e. after factoring). Comparison of the overbreak figures between Tables 1 and 2 suggests that although panel type may be an issue there must be other significant factors.

11.3 Overbreak as a Function of Excavation Time

Figures 5 and 6 have been extracted from the Diaphragm Wall Construction Records (Table 2). In these two figures the overbreak is plotted as a function of the excavation time for excavation in Earth (Figure 5) and Rock (Figure 6). For Figures 5 and 6 the overbreak recorded in the data sheets has been reduced by a uniform factor of 1.3 for all opening panels. This factor could be refined if the excavated length of all the panels was known (NB the data set for Figures 1 to 4, see Table 1, is for the most part different to that for Figures 5 and 6, see Table 2, though there are some common panels between the two sets)

Best fit lines have been plotted for opening and running panels in both Figures 5 and 6. The lines show:

| | Overbreak for zero time | Increase in overbreak per hour of excavation | Correlation coefficient R |
|---------------------|------------------------------------|---|--|
| Excavation in Earth | | | |
| Opening panels | 43.1 | -0.10 | 0.009 |
| Running panels | 24.3 | -1.23 | 0.14 |
| Excavation in Rock | | | |
| Opening panels | 19.1 | 3.74 | 0.38 |
| Running panels | 14.4 | 1.09 | 0.23 |

The correlation coefficient is a measure of the correlation between the variables overbreak and excavation time. If the correlation were perfect then the correlation coefficient would be +/-1.0. The actual values are much less than 1.0 and imply poor correlation especially for the Earth excavation where the best fit lines suggest that the overbreak slightly reduces with increasing excavation time. However, the correlation coefficients for the lines are so low that no credence should be given to any trend and it would be more reasonable to say that the parameters show no useful correlation.

In the above summary the overbreak at zero time is the intercept of the best fit line on the overbreak axis at zero time. The relative magnitude of the overbreak at zero time and the rate of increase of overbreak with excavation time i.e. the ratio of the intercept to the slope of the graph gives an indication of the significance of the excavation time. It can be seen that the overbreak at time zero is generally much greater than the effect several hours of churn drilling.

11.4 Identification of the Location and Geometry of the Overbreak Voids

It is understood that the recommendation that an ultrasonic unit be obtained to investigate the void has been actioned and that it is now on site.

12. HOLDING DOWN THE CAGES

There is always a risk of the cages lifting during concreting. Holding down cages is now so much part of diaphragm wall construction that procedures can pass unnoticed. It would seem that on the Highway 416 project it was not so much a matter of passing unnoticed but of being ignored. In the UK a typical procedure is to set loops of reinforcing steel in guide walls. Once the cage is in place holding down bars are then passed through these loops and fixed to them. The cages are then, in turn, fixed to the bars. In this way multiple hold down points can be applied to any cage. Of course the cage has to be designed to be held at intervals along its length. The loops are also very useful for lifting the guide walls if / when they are removed.

It may be noted that Xanthakos (1979) one of rather few books on diaphragm walls states in relation to reinforcing cages with boxes and inserts:

‘No particular difficulties should be encountered in positioning insert boxes if they are robust and firmly attached to the cage, provided the cage itself is accurately positioned and firmly held’.

He thus specifically confirms the need to firmly restrain the cage.

13. CONCLUSIONS REGARDING THE DIAPHRAGM WALL

The recorded data for the fresh excavation slurry show that it is unexceptional and would meet most excavation slurry specifications. I have seen and reviewed only limited data on slurry samples from the trench (pH, density, fluid loss and sand content results are reported but only a few viscosity values and no shear strengths). The data again seem satisfactory. Thus as regards excavation the slurry properties are reasonable and it would be difficult to attribute the observed high overbreaks to poor quality slurry. However, for both concreting and excavation there are concerns that the results are not for the slurry at depth in the trench and that the sampler begins to fill when submerged by at most a few metres.

There is also concern that the slurry level is not sufficiently above the ground water level to ensure stability of the trench. In particular it would seem that the difference in level between the excavation slurry and the ground water is frequently less than the 1 m required in many specifications.

From an analysis of the overbreak as a function of depth it appears that there is no clear correlation with either height from the base of the trench or depth below ground (guide wall level). The influence of soil type has not been investigated and could warrant some analysis.

An investigation of overbreak as a function of excavation time shows no significant correlation for the excavation in soil. In the rock there is some correlation but the rate of increase of overbreak with churn drilling time is small compared to the overbreak that occurs irrespective of drilling time (i.e. the intercept on the overbreak axis).

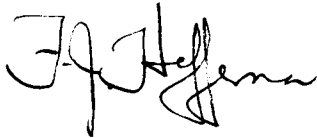
There is also concern about the performance of the sampler in relation to concreting. Failure of the sampler to collect samples from the deeper levels in a trench could mean that concrete is being placed through inappropriately dense slurry - the core holes drilled while I was on site showed some evidence of slurry remaining on the reinforcing steel.

14. REFERENCES

Federation of Piling Specialists, Specification for cast in place concrete diaphragm walling, Ground Engineering, UK, Vol. 6, No. 4, 1973.

Xanthakos, Slurry Walls, McGraw Hill Book Company, 1979

GOLDER ASSOCIATES LTD.



S. A. Jefferis, Ph.D.
Associate

951-1120.LR1

| | | Depth | Theoretical | Concrete | Average | Height | Average | Factored | Overall |
|----------------------------|-------|-------|-------------|----------|---------|------------------------|-----------|-----------|-----------|
| | | | Volume | Volume | Depth | from base (average) | Overbreak | Overbreak | Overbreak |
| Running Panels | | | | | | | | | |
| Panel No | W58 | | | | | | | | |
| Theoretical vol | 35.00 | 9.3 | 0.00 | 0.00 | | | 0.0 | | 44.3 |
| Effective area | 3.76 | 6.5 | 10.54 | 16.00 | 7.90 | 1.40 | 51.8 | 51.8 | |
| Theoretical area concreted | 3.75 | 3.8 | 10.16 | 16.00 | 5.15 | 4.15 | 57.5 | 57.5 | |
| Panel type | R | 0.6 | 12.04 | 16.00 | 2.20 | 7.10 | 32.9 | 32.9 | |
| Theoretical length | 5.02 | 0.0 | 2.26 | 2.50 | 0.30 | 9.00 | 10.7 | 10.7 | |
| Factor | 1.00 | | | | | | | | |
| | | | | | | | | | |
| Panel No | W52 | | | | | | | | |
| Theoretical vol | 33.75 | 9.0 | 0.00 | 0.00 | | | 0.0 | | 83.7 |
| Effective area | 3.75 | 6.9 | 7.88 | 16.00 | 7.95 | 1.05 | 103.2 | 103.2 | |
| Theoretical area concreted | 3.75 | 5.8 | 4.13 | 15.00 | 6.35 | 2.65 | 263.6 | 263.6 | |
| Panel type | R | 2.8 | 11.25 | 17.00 | 4.30 | 4.70 | 51.1 | 51.1 | |
| Theoretical length | 5.00 | 0.0 | 10.50 | 14.00 | 1.40 | 7.60 | 33.3 | 33.3 | |
| Factor | 1.00 | | | | | | | | |
| | | | | | | | | | |
| Panel No | W61 | | | | | | | | |
| Theoretical vol | 37.50 | 10.1 | 0.00 | 0.00 | | | 0.0 | | 28.0 |
| Effective area | 3.71 | 6.7 | 12.62 | 17.00 | 8.40 | 1.70 | 34.7 | 34.7 | |
| Theoretical area concreted | 3.75 | 3.6 | 11.51 | 17.00 | 5.15 | 4.95 | 47.7 | 47.7 | |
| Panel type | R | 0.0 | 13.37 | 14.00 | 1.80 | 8.30 | 4.7 | 4.7 | |
| Theoretical length | 4.95 | | | | | | | | |
| Factor | 1.00 | | | | | | | | |
| | | | | | | | | | |
| Panel No | W63 | | | | | | | | |
| Theoretical vol | 33.00 | 9.8 | 0.00 | 0.00 | | | 0.0 | | 45.5 |
| Effective area | 3.37 | 6.8 | 10.10 | 16.00 | 8.30 | 1.50 | 58.4 | 58.4 | |
| Theoretical area concreted | 3.38 | 4.0 | 9.43 | 16.00 | 5.40 | 4.40 | 69.7 | 69.7 | |
| Panel type | R | 2.3 | 5.89 | 8.00 | 3.13 | 6.68 | 35.8 | 35.8 | |
| Theoretical length | 4.49 | 0.3 | 6.57 | 8.00 | 1.28 | 8.53 | 21.8 | 21.8 | |
| Factor | 1.00 | | | | | | | | |
| | | | | | | | | | |
| Panel No | W64 | | | | | | | | |
| Theoretical vol | 37.00 | 9.9 | 0.00 | 0.00 | | | 0.0 | | 40.5 |
| effective area | 3.74 | 6.9 | 11.21 | 16.00 | 8.40 | 1.50 | 42.7 | 42.7 | |
| Theoretical area concreted | 3.68 | 3.8 | 11.77 | 16.00 | 5.33 | 4.58 | 35.9 | 35.9 | |
| Panel type | R | 0.7 | 11.40 | 16.00 | 2.23 | 7.68 | 40.4 | 40.4 | |
| Theoretical length | 4.98 | 0.0 | 2.62 | 4.00 | 0.35 | 9.55 | 52.9 | 52.9 | |
| Pay vol | 35.02 | | | | | | | | |
| Factor | 1.00 | | | | | | | | |
| | | | | | | | | | |
| Panel No | W67 | | | | | | | | |
| Theoretical vol | 32.00 | 8.5 | 0.00 | 0.00 | | | 0.0 | | 37.5 |
| Effective area | 3.76 | 5.9 | 9.79 | 16.00 | 7.20 | 1.30 | 63.5 | 63.5 | |
| Theoretical area concreted | 3.75 | 2.0 | 14.68 | 16.00 | 3.95 | 4.55 | 9.0 | 9.0 | |
| Panel type | R | 0.0 | 7.53 | 12.00 | 1.00 | 7.50 | 59.4 | 59.4 | |
| Theoretical length | 5.02 | | | | | | | | |
| Pay vol | 30.45 | | | | | | | | |
| Factor | 1.00 | | | | | | | | |
| | | | | | | | | | |

Table 1: Concreting Data

| | | Depth | Theoretical | Concrete | Average | Height | Average | Factored | Overall |
|----------------------------|-------|-------|-------------|----------|---------|------------------------|-----------|-----------|-----------|
| | | | Volume | Volume | Depth | from base (average) | Overbreak | Overbreak | Overbreak |
| Panel No | E4 | | | | | | | | |
| Theoretical vol | 45.00 | 12.0 | | | | | 0.0 | | 75.6 |
| Effective area | 3.75 | 9.0 | 11.25 | 16.00 | 10.50 | 1.50 | 42.2 | 42.2 | |
| Theoretical area concreted | 3.60 | 6.3 | 10.13 | 16.00 | 7.65 | 4.35 | 58.0 | 58.0 | |
| Panel type | R | 5.0 | 4.88 | 16.00 | 5.65 | 6.35 | 228.2 | 228.2 | |
| Theoretical length | 5.00 | 2.5 | 9.38 | 16.00 | 3.75 | 8.25 | 70.7 | 70.7 | |
| Factor | 1.00 | 1.0 | 5.63 | 8.00 | 1.75 | 10.25 | 42.2 | 42.2 | |
| | | 0.0 | 3.75 | 7.00 | 0.50 | 11.50 | 86.7 | 86.7 | |
| Panel No | E6 | | | | | | | | |
| Theoretical vol | 45.00 | 12.0 | 0.00 | 0.00 | | | 0.0 | | 55.6 |
| Effective area | 3.75 | 10.0 | 7.50 | 16.00 | 11.00 | 1.00 | 113.3 | 113.3 | |
| Theoretical area concreted | 3.75 | 7.0 | 11.25 | 16.00 | 8.50 | 3.50 | 42.2 | 42.2 | |
| Panel type | R | 4.5 | 9.38 | 16.00 | 5.75 | 6.25 | 70.7 | 70.7 | |
| Theoretical length | 5.00 | 3.0 | 5.63 | 8.00 | 3.75 | 8.25 | 42.2 | 42.2 | |
| Factor | 1.00 | 1.1 | 7.13 | 8.00 | 2.05 | 9.95 | 12.3 | 12.3 | |
| | | 0.0 | 4.13 | 6.00 | 0.55 | 11.45 | 45.5 | 45.5 | |
| Opening Panels | | | | | | | | | |
| Panel No | W10 | | | | | | | | |
| Theoretical vol | 55.00 | 14.6 | 0.00 | 0.00 | | | 0.0 | | 40.0 |
| Effective area | 3.78 | 11.8 | 10.40 | 18.00 | 13.18 | 1.38 | 73.2 | 56.3 | |
| Theoretical area concreted | 3.87 | 9.8 | 7.56 | 14.00 | 10.80 | 3.75 | 85.2 | 65.5 | |
| Panel type | O | 6.8 | 11.34 | 16.00 | 8.30 | 6.25 | 41.1 | 31.6 | |
| Theoretical length | 5.04 | 3.3 | 13.42 | 16.00 | 5.03 | 9.53 | 19.2 | 14.8 | |
| Factor | 1.30 | 1.8 | 5.67 | 8.00 | 2.50 | 12.05 | 41.1 | 31.6 | |
| | | 0.7 | 3.97 | 5.00 | 1.23 | 13.33 | 26.0 | 20.0 | |
| Panel No | W19 | | | | | | | | |
| Theoretical vol | 50.00 | 13.4 | 0.00 | 0.00 | | | 0.0 | | 75.0 |
| Effective area | 3.75 | 10.8 | 9.55 | 17.00 | 12.08 | 1.28 | 78.0 | 60.0 | |
| Theoretical area concreted | 3.87 | 9.0 | 6.74 | 17.00 | 9.90 | 3.45 | 152.2 | 117.1 | |
| Panel type | O | 7.8 | 4.49 | 14.00 | 8.40 | 4.95 | 211.5 | 162.7 | |
| Theoretical length | 4.99 | 6.8 | 3.75 | 8.00 | 7.30 | 6.05 | 113.6 | 87.4 | |
| Factor | 1.30 | 5.4 | 5.24 | 8.00 | 6.10 | 7.25 | 52.6 | 40.4 | |
| | | 3.8 | 5.99 | 8.00 | 4.60 | 8.75 | 33.5 | 25.8 | |
| | | 2.0 | 6.74 | 8.00 | 2.90 | 10.45 | 18.7 | 14.4 | |
| | | 1.1 | 3.30 | 7.50 | 1.56 | 11.79 | 127.6 | 98.1 | |
| Panel No | W24 | | | | | | | | |
| Theoretical vol | 50.00 | 13.3 | 0.00 | 0.00 | | | 0.0 | | 78.0 |
| Effective area | 3.77 | 11.0 | 8.49 | 16.00 | 12.13 | 1.13 | 88.4 | 68.0 | |
| Theoretical area concreted | 3.87 | 9.3 | 6.60 | 18.00 | 10.13 | 3.13 | 172.6 | 132.7 | |
| Panel type | O | 7.8 | 5.47 | 14.00 | 8.53 | 4.73 | 155.9 | 119.9 | |
| Theoretical length | 5.03 | 6.9 | 3.40 | 8.00 | 7.35 | 5.90 | 135.6 | 104.3 | |
| Pay volume | 43.78 | 5.9 | 3.77 | 5.00 | 6.40 | 6.85 | 32.5 | 25.0 | |
| Pay length | 5.00 | 2.9 | 11.32 | 19.00 | 4.40 | 8.85 | 67.8 | 52.2 | |
| Factor | 1.30 | 1.6 | 5.09 | 9.00 | 2.23 | 11.03 | 76.7 | 59.0 | |
| Panel No | W31 | | | | | | | | |
| Theoretical vol | 47.00 | 12.5 | 0.00 | 0.00 | | | 0.0 | | 36.2 |

Table 1: Concreting Data

| | | Depth | Theoretical | Concrete | Average | Height | Average | Factored | Overall |
|----------------------------|-------|-------|-------------|----------|---------|------------------------|-----------|-----------|-----------|
| | | | Volume | Volume | Depth | from base (average) | Overbreak | Overbreak | Overbreak |
| Effective area | 3.76 | 10.5 | 7.52 | 17.00 | 11.50 | 1.00 | 126.1 | 97.0 | |
| Theoretical area concreted | 3.87 | 8.1 | 9.02 | 14.00 | 9.30 | 3.20 | 55.1 | 42.4 | |
| Panel type | 0 | 4.9 | 12.03 | 17.00 | 6.50 | 6.00 | 41.3 | 31.8 | |
| Theoretical length | 5.01 | 1.7 | 12.03 | 16.00 | 3.30 | 9.20 | 33.0 | 25.4 | |
| Factor | 1.30 | | | | | | | | |
| Panel No | W37 | | | | | | | | |
| Theoretical vol | 44.00 | 12.0 | 0.00 | 0.00 | | | 0.0 | | 40.9 |
| Effective area | 3.67 | 9.2 | 10.27 | 17.00 | 10.60 | 1.40 | 65.6 | 50.2 | |
| Theoretical area concreted | 3.87 | 6.5 | 9.90 | 16.00 | 7.85 | 4.15 | 61.6 | 47.1 | |
| Panel type | 0 | 4.0 | 9.17 | 15.00 | 5.25 | 6.75 | 63.6 | 48.7 | |
| Theoretical length | 4.89 | 2.7 | 4.77 | 8.00 | 3.35 | 8.65 | 67.8 | 51.9 | |
| Factor | 1.31 | 1.4 | 4.77 | 6.00 | 2.05 | 9.95 | 25.9 | 19.8 | |
| Panel No | W51 | | | | | | | | |
| Theoretical vol | 34.00 | 9.1 | 0.00 | 0.00 | | | 0.0 | | 41.2 |
| Effective area | 3.74 | 6.6 | 9.34 | 17.00 | 7.85 | 1.25 | 82.0 | 63.1 | |
| Theoretical area concreted | 3.87 | 4.0 | 9.71 | 17.00 | 5.30 | 3.80 | 75.0 | 57.7 | |
| Panel type | 0 | 0.9 | 11.58 | 14.00 | 2.45 | 6.65 | 20.9 | 16.1 | |
| Theoretical length | 4.98 | | | | | | | | |
| Factor | 1.30 | | | | | | | | |
| Closing Panels | | | | | | | | | |
| Panel No | W62 | | | | | | | | |
| Theoretical vol | 35.00 | 9.8 | 0.00 | 0.00 | | | 0.0 | | 34.3 |
| Effective area | 3.57 | 6.8 | 10.71 | 14.00 | 8.30 | 1.50 | 30.7 | 44.8 | |
| Theoretical area concreted | 3.72 | 4.0 | 10.00 | 14.00 | 5.40 | 4.40 | 40.0 | 58.4 | |
| Panel type | C | 1.0 | 10.71 | 14.00 | 2.50 | 7.30 | 30.7 | 44.8 | |
| Theoretical length | 4.76 | 0.0 | 3.57 | 5.00 | 0.50 | 9.30 | 40.0 | 58.4 | |
| Factor | 0.69 | | | | | | | | |
| Panel No | W68 | | | | | | | | |
| Theoretical vol | 30.00 | 8.2 | 0.00 | 0.00 | | | 0.0 | | 13.3 |
| Effective area | 3.66 | 5.1 | 11.34 | 15.00 | 6.65 | 1.55 | 32.3 | 46.6 | |
| Theoretical area concreted | 3.57 | 0.7 | 16.10 | 16.00 | 2.90 | 5.30 | -0.6 | -0.9 | |
| Panel type | C | 0.0 | 2.56 | 3.00 | 0.35 | 7.85 | 17.1 | 24.8 | |
| Theoretical length | 4.88 | | | | | | | | |
| Pay vol | 29.66 | | | | | | | | |
| Factor | 0.69 | | | | | | | | |
| Panel No | E1 | | | | | | | | |
| Theoretical vol | 38.00 | 11.7 | 0.00 | 0.00 | | | 0.0 | | 39.5 |
| Effective area | 3.25 | 8.4 | 10.72 | 17.00 | 10.05 | 1.65 | 58.6 | 88.3 | |
| Theoretical area concreted | 3.35 | 5.0 | 11.04 | 14.00 | 6.70 | 5.00 | 26.8 | 40.3 | |
| Panel type | C | 1.1 | 12.67 | 17.00 | 3.05 | 8.65 | 34.2 | 51.5 | |
| Pay vol | 43.03 | 0.0 | 3.57 | 5.00 | 0.55 | 11.15 | 40.0 | 60.2 | |
| Theoretical length | 4.46 | | | | | | | | |
| Factor | 0.66 | | | | | | | | |
| Panel No | E5 | | | | | | | | |
| Theoretical vol | 46.00 | 12.0 | | | | | 0.0 | | 21.7 |

Table 1: Concreting Data

| | | Depth | Theoretical | Concrete | Average | Height | Average | Factored | Overall |
|-----------------------------------|-------|-------|-------------|-----------------|---------|-----------|-----------|-----------|-----------|
| | | | Volume | Volume | Depth | from base | Overbreak | Overbreak | Overbreak |
| | | | | | | (average) | | | |
| Effective area | 3.83 | 9.1 | 11.12 | 14.00 | 10.55 | 1.45 | 25.9 | 37.1 | |
| Theoretical area concreted | 4.31 | 6.0 | 11.88 | 16.00 | 7.55 | 4.45 | 34.6 | 49.5 | |
| Panel type | C | 2.3 | 14.38 | 17.00 | 4.13 | 7.88 | 18.3 | 26.1 | |
| Theoretical length | 5.11 | 0.0 | 8.63 | 9.00 | 1.13 | 10.88 | 4.3 | 6.2 | |
| Factor | 0.70 | | | | | | | | |
| | | | | | | | | | |
| Panel No | W57 | | | | | | | | |
| Theoretical vol | 39.00 | 9.3 | 0.00 | 0.00 | | | 0.0 | | 56.4 |
| Effective area | 4.22 | 6.5 | 11.59 | 16.00 | 7.88 | 1.38 | 38.0 | 51.8 | |
| Theoretical area concreted | 4.32 | 4.6 | 8.01 | 16.00 | 5.55 | 3.70 | 99.7 | 136.0 | |
| Panel type | C | 2.4 | 9.28 | 16.00 | 3.50 | 5.75 | 72.5 | 98.9 | |
| Theoretical length | 5.62 | 0.8 | 6.75 | 8.00 | 1.60 | 7.65 | 18.6 | 25.4 | |
| Factor | 0.73 | 0.0 | 3.37 | 5.00 | 0.40 | 8.85 | 48.2 | 65.8 | |
| | | | | | | | | | |
| Panel No | W53 | | | | | | | | |
| Theoretical vol | 28.50 | 8.9 | 0.00 | 0.00 | | | 0.0 | | 24.6 |
| Effective area | 3.22 | 5.0 | 12.40 | 17.00 | 6.93 | 1.93 | 37.1 | 57.0 | |
| Theoretical area concreted | 3.35 | 1.0 | 12.88 | 14.00 | 3.00 | 5.85 | 8.7 | 13.3 | |
| Panel type | C | 0.0 | 3.22 | 4.50 | 0.50 | 8.35 | 39.7 | 61.1 | |
| Theoretical length | 4.29 | | | | | | | | |
| Factor | 0.65 | | | | | | | | |
| | | | | | | | | | |
| | | | | Average Factors | | | | | |
| Average overbreaks | | | | | | | | | |
| Average overbreak, Opening panels | | | 51.88 | 1.01 | | | | | |
| Average overbreak, Running panels | | | 51.32 | 1.00 | | | | | |
| Average overbreak, Closing panels | | | 31.63 | 0.62 | | | | | |
| | | | | | | | | | |

Table 1: Concreting Data

Notes to Table 1

The data given in Table 1 are taken from Petrifond's Concreting Reports (Rapport de Betonnage).

In Table 1 the Theoretical Volume is the volume of the trench to the top of the guide wall as presented in the Concreting Reports. If the concreting record has been stopped short of the top of the guide wall the Theoretical Volume is the extrapolation of the theoretical volume line (of the Concreting Report) to the top of the guide wall (see for example the record for Panel W31 for which the theoretical line terminates at a depth of about 1.7 m below the top of the guide wall).

The Effective Area is the area calculated from the Theoretical Volume and the overall depth of the panel taken from the Concreting Reports. As the nominal length of each panel is 5 m and the nominal width is 750 mm the Effective area for a 'standard' panel should be 3.75 m² (ignoring the curvature at the ends of the panel). It can be seen that for many of the panels the Effective area is at or close to this value and thus it would seem that Petrifond have ignored the effect of the curved areas at the ends of the panels for the Opening and Closing panels (for the Running panels the curvatures at either end are opposed and their effects cancel out).

The Theoretical Area is included as a check and is the product of the nominal thickness of the panel (750 mm) and the length of the panel as given in the Diaphragm Wall Panel Summary sheets which accompany the Concreting Records or the estimated length of the panel where no summary sheet is available.

The Panel Type is O - Opening, R - Running, C - Closing.

The Theoretical Length is a check figure and has been calculated by dividing the Effective Area by the nominal thickness of the wall. No allowance has been made for the curvature of the panel at the ends due to the use of circular stop ends.

The Pay Volume has been calculated for a few panels as a check. Petrifond list the Pay Volume in the Diaphragm Wall Panel Summary sheets. This volume appears to be the volume of concrete between the base of the panel and the final trim level. The length used in the calculation would appear to be the nominal; length of the panel rather than the actual length as given in the Diaphragm Wall Panel Summary sheets which are included at the end of the Concreting Records.

The Factor, as detailed in the text is the ratio of the excavated length to the concreted length. The overbreak calculated by length of wall concreted must be divided by the factor to get the overbreak per unit length of excavation. Where the theoretical length is found to be about 5 m the factors for the Opening, Running and Closing panels have been assumed to be 1.3, 1 and 0.7 respectively (i.e. $(5 + 1.5) / 5$, 1 and $(5 - 1.5) / 5$). Where the Theoretical length is markedly different from 5 m the actual value is used in place of 5 m in the calculation of the factor.

The Depth and Concrete Volume (poured) data are taken from the Concreting Reports. The Average Overbreak is the average overbreak between successive depth soundings in the panel and is calculated from the Effective Area of the panel. The Average Depth is the average depth between successive depth soundings.

The Height from base is the average height of each section of average overbreak as measured upwards from the base of the trench rather than downwards from the top of the guide wall.

The Factored Overbreak is the Average Overbreak divided by the Factor.

The Overall Overbreak is the total Volume of Concrete divided by the Theoretical Volume. It has not been factored.

| Panel No | Type | Factor | Total | Factored | Factored | Time, hours | | Time, hours | | Time |
|--|------|--------|-----------|-----------|-----------|-------------|---------|-------------|---------|-------|
| | | | Overbreak | Overbreak | Overbreak | Earth | Rock | Earth | Rock | Hours |
| | | | | Opening | Running | Opening | Opening | Running | Running | Total |
| W37 | O | 1.3 | 49 | 38 | | 3 | 4.5 | | | 7.5 |
| W31 | O | 1.3 | 38 | 29 | | 2.5 | 5.5 | | | 8 |
| W24 | O | 1.3 | 79 | 61 | | 4 | 7 | | | 11 |
| W19 | O | 1.3 | 74 | 57 | | 4.5 | 8.5 | | | 13 |
| W10 | O | 1.3 | 41 | 32 | | 7.75 | 7.25 | | | 15 |
| W3 | O | 1.3 | 20 | 15 | | 3.75 | 5 | | | 8.75 |
| W36 | R | 1 | 7 | | 7 | | | 5.5 | 3.5 | 9 |
| W30 | R | 1 | 17 | | 17 | | | 4.75 | 2.25 | 7 |
| W23 | R | 1 | 17 | | 17 | | | 3 | 3.25 | 6.25 |
| W9 | R | 1 | 19 | | 19 | | | 4.75 | 2 | 6.75 |
| W18 | R | 1 | 25 | | 25 | | | 3.5 | 3 | 6.5 |
| W2 | R | 1 | 16 | | 16 | | | 3.5 | 4.75 | 8.25 |
| W4 | R | 1 | 11 | | 11 | | | 3 | 4 | 7 |
| W11 | R | 1 | 14 | | 14 | | | 3 | 7.75 | 10.75 |
| E28 | O | 1.3 | 57 | 44 | | 2.5 | 5 | | | 7.5 |
| E34 | O | 1.3 | 59 | 45 | | 3.25 | 5.5 | | | 8.75 |
| E41 | O | 1.3 | 78 | 60 | | 3 | 7.5 | | | 10.5 |
| E48 | O | 1.3 | 66 | 51 | | 3.5 | 7.5 | | | 11 |
| E53 | O | 1.3 | 49 | 38 | | 4 | 8.5 | | | 12.5 |
| W35 | R | 1 | 13 | | 13 | | | 5.5 | 4 | 9.5 |
| W29 | R | 1 | 18 | | 18 | | | 3.5 | 4.25 | 7.75 |
| W22 | R | 1 | 23 | | 23 | | | 3.5 | 8.25 | 11.75 |
| W8 | R | 1 | 23 | | 23 | | | 5.75 | 6.5 | 12.25 |
| W17 | R | 1 | 44 | | 44 | | | 3.75 | 6.75 | 10.5 |
| E38 | O | 1.3 | 70 | 54 | | 4.25 | 6 | | | 10.25 |
| E31 | O | 1.3 | 33 | 25 | | 2.5 | 6 | | | 8.5 |
| E45 | O | 1.3 | 64 | 49 | | 3.5 | 4.5 | | | 8 |
| W34 | R | 1 | 13 | | 13 | | | 3 | 4.5 | 7.5 |
| W28 | R | 1 | 18 | | 18 | | | 3.5 | 6 | 9.5 |
| W21 | R | 1 | 17 | | 17 | | | 2.5 | 7.25 | 9.75 |
| W16 | R | 1 | 34 | | 34 | | | 3.25 | 4 | 7.25 |
| W7 | R | 1 | 25 | | 25 | | | 3 | 5 | 8 |
| E29 | R | 1 | 46 | | 46 | | | | | 0 |
| E35 | R | 1 | 43 | | 43 | | | | | 0 |
| Maximum | | | 79.0 | 61 | 46.0 | 7.8 | 8.5 | 5.8 | 8.3 | |
| Minimum | | | 7.0 | 15 | 7.0 | 2.5 | 4.5 | 2.5 | 2.0 | |
| Average | | | 36.7 | 46 | 23.3 | 4.2 | 6.7 | 3.9 | 5.0 | |
| Standard deviation | | | 23.3 | 14 | 12.1 | 1.7 | 1.4 | 1.1 | 2.0 | |
| Ratio of average unfactored overbreaks Opening/Running | | | | | | | 2.5 | | | |

Table 2: Diaphragm Wall Construction (South Side) Records

Overbreak as a function of Depth for Opening, Running and Closing Panels

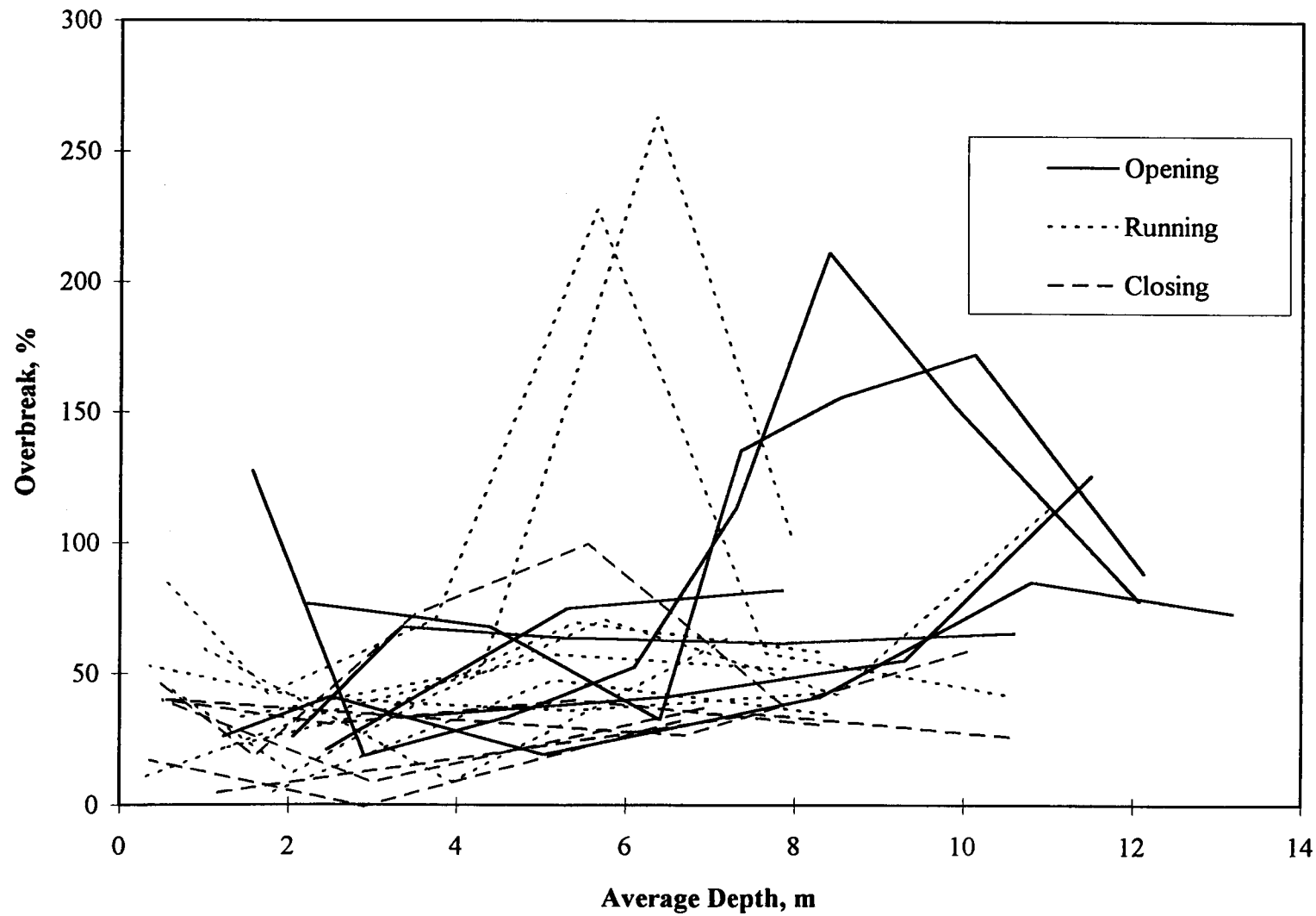


Figure 1

Overbreak as a function of Height for Opening, Running and Closing Panels

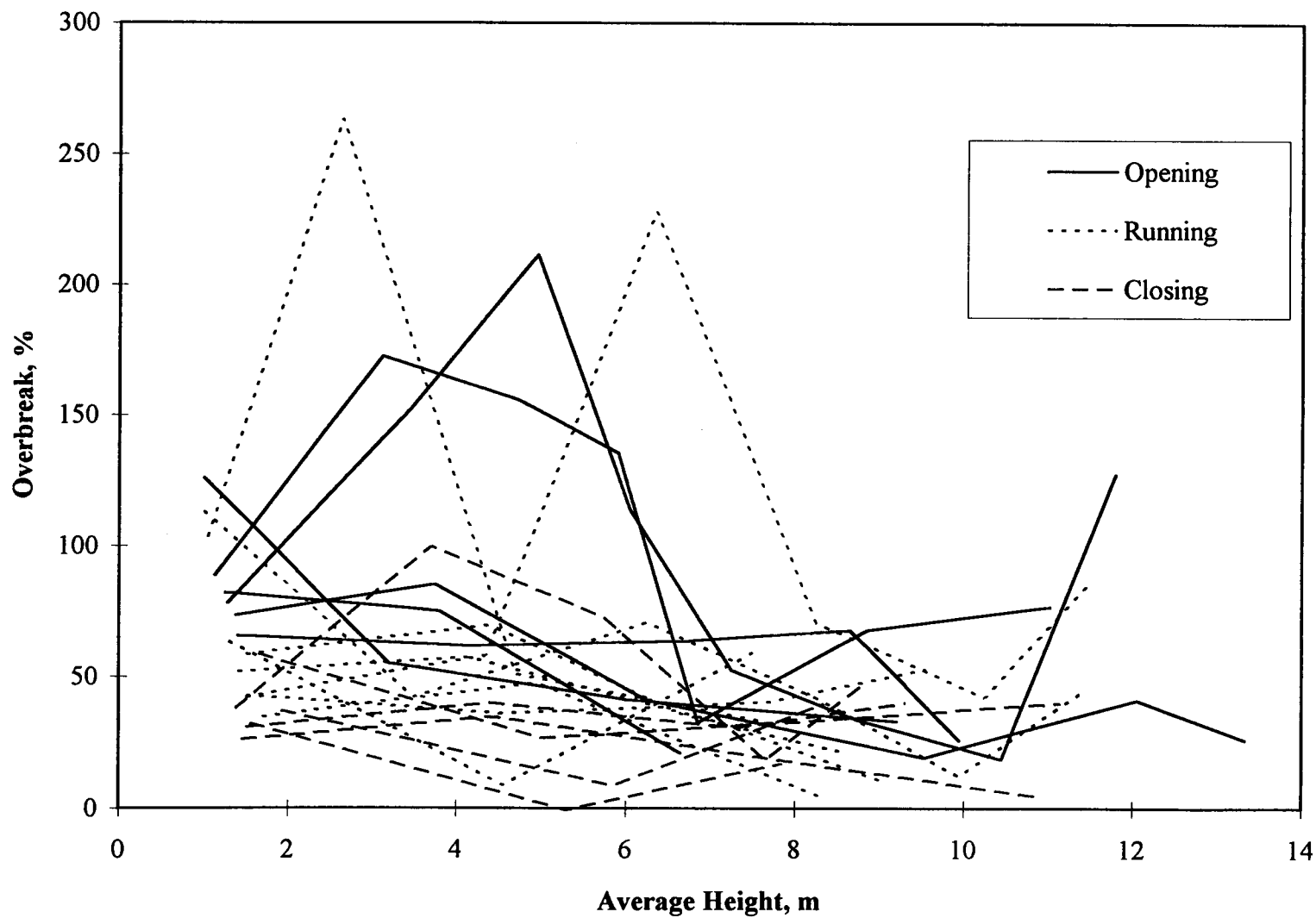


Figure 2

Factored Overbreak as a function of Depth for Opening, Running and Closing Panels

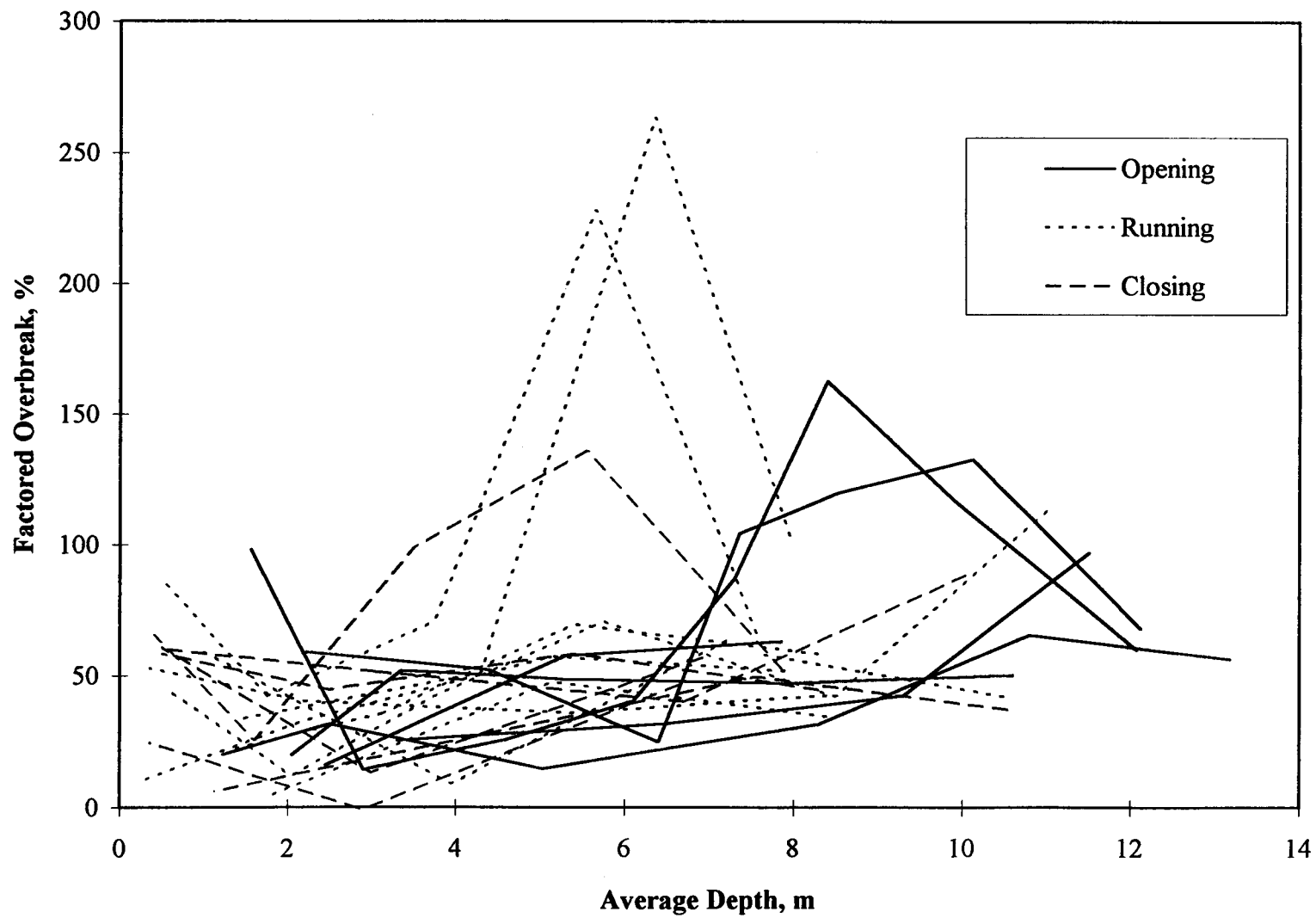


Figure 3

Factored Overbreak as a function of Height for Opening, Running and Closing Panels

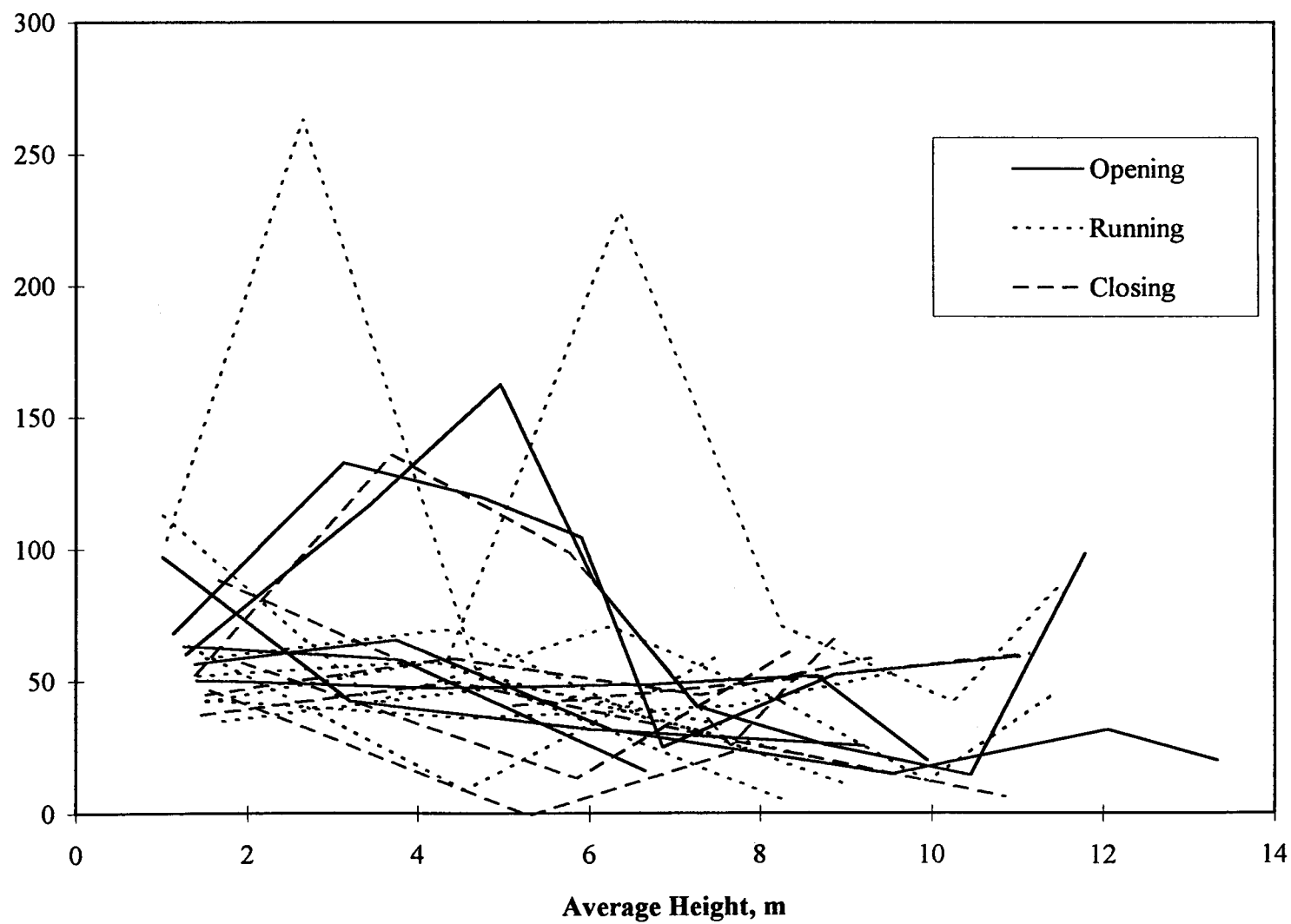


Figure 4

Diaphragm Wall Construction (South Side) Records

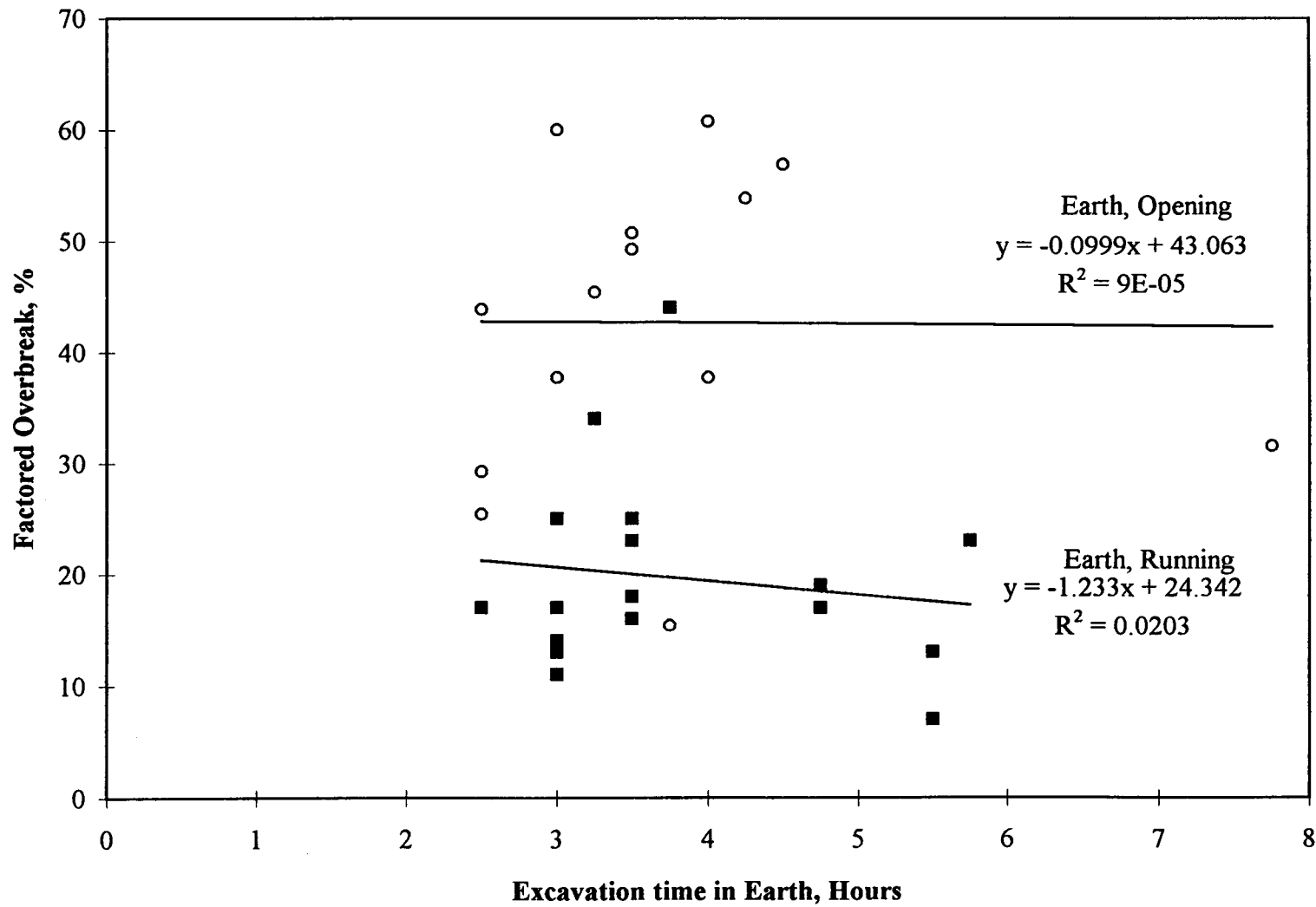


Figure 5

Diaphragm Wall Construction (South Side) Records

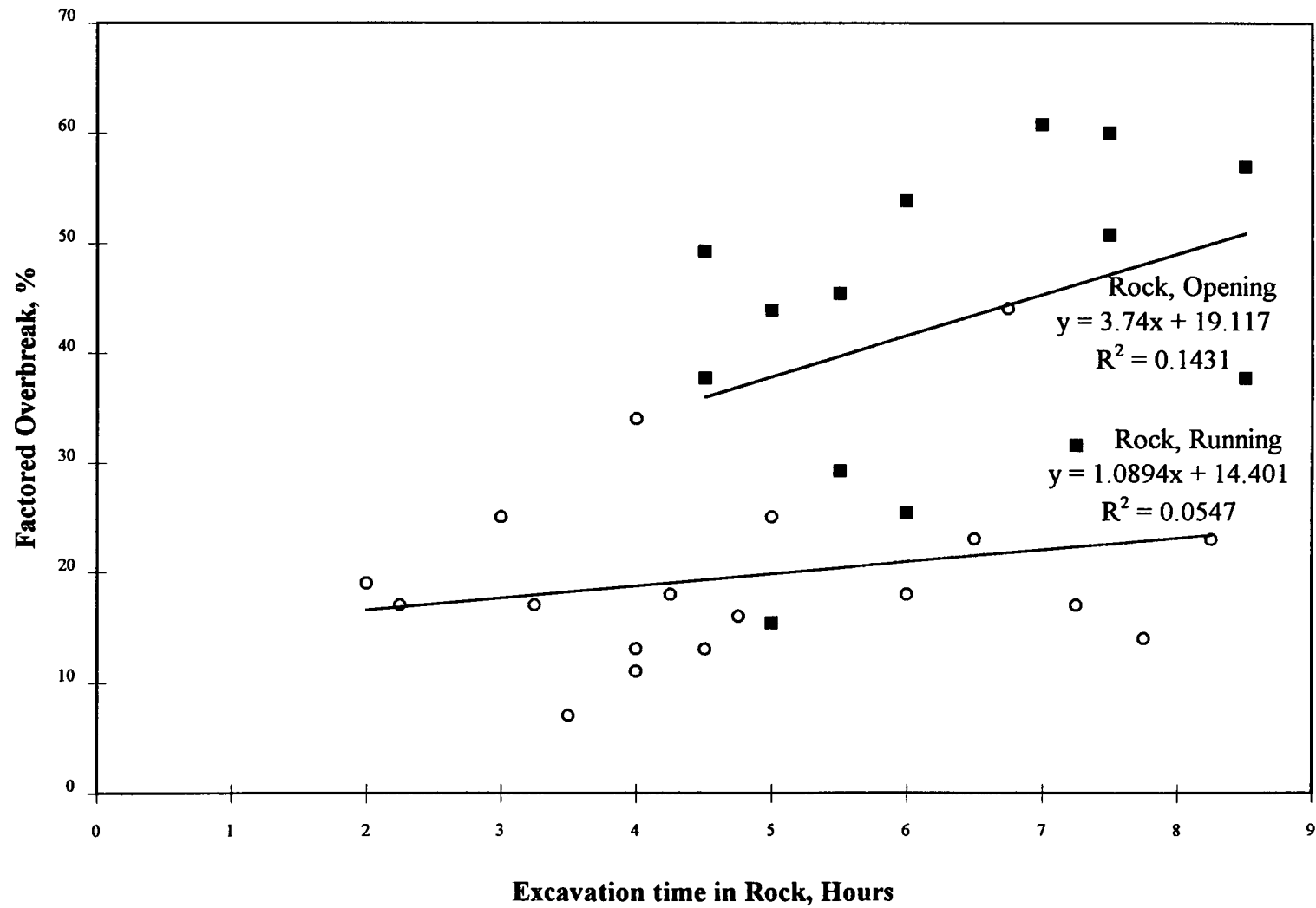


Figure 6

Total Overbreak as a function of Total excavation time

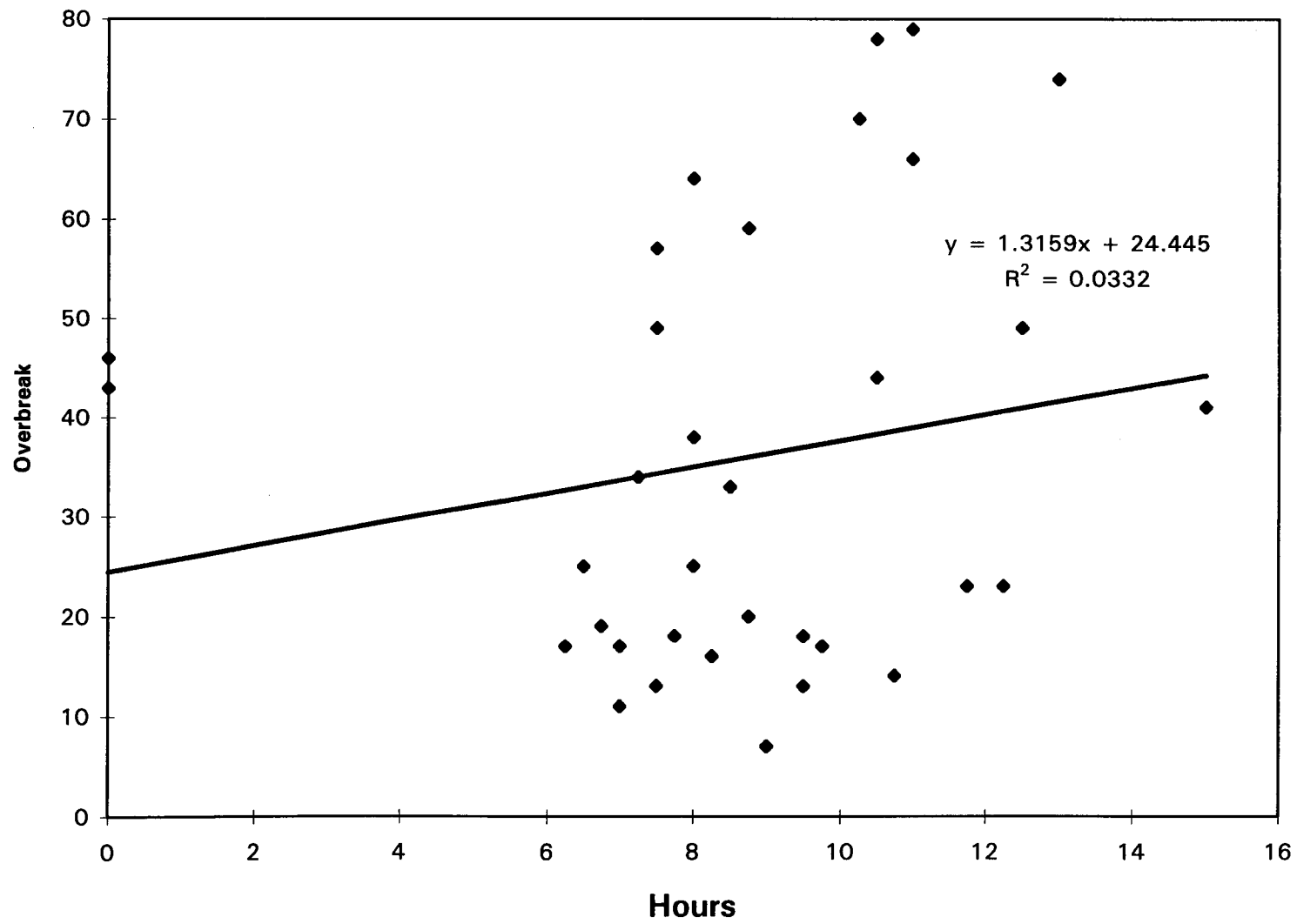


Figure 7

APPENDIX 1

THE SLURRY SAMPLING DEVICE

APPENDIX 1

The Slurry Sampling Device

Figure A1 shows a schematic diagram of Petrifond's slurry sampling device. The device consists of a tube of order 120 mm in diameter sealed at the lower end. The top is sealed with a screw cap. This cap has a central opening which can be closed by a plunger which can be pulled up against a sealing washer inside the cap. The device has two ropes attached to it. Rope C (closing) attached to a ring at the top of the plunger, marked 'C' in Figure A1 and Rope F (filling) attached to the body of the sampler. In operation the device is suspended from Rope C. In this situation the weight of the tube holds the top cap sealed against the plunger. The sampler is lowered into the trench on Rope C and when it is at the required depth the Rope is slackened and the weight transferred to Rope F. The slurry should then invade the sampler chamber and displace any trapped air.

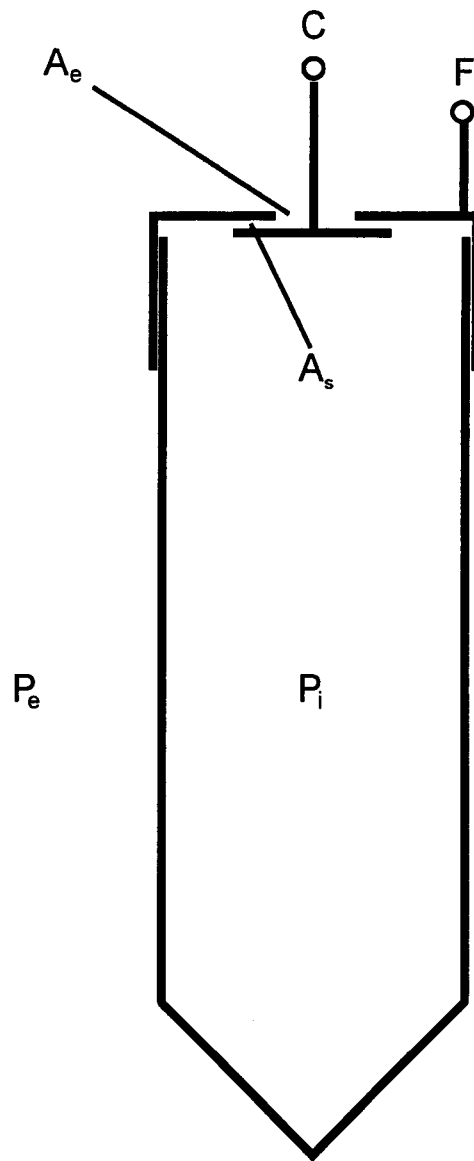
It should be noted that it is the effective weight, W of the sampler when immersed in slurry (but still air filled) that seals the plunger to the top cap. This weight will be quite modest and insufficient to seal the sampler at depth in the trench. This can be demonstrated by analysing the forces acting on the system from which it can be shown that the maximum depth, d to which the sampler can be immersed in a slurry of density γ_s is given by:

$$d = (W + A_s (P_i - P_s)) / A_e \gamma_s(1)$$

where: A_e is the external area of the plunger exposed to the slurry, P_i is the pressure inside the sampler (atmospheric until some slurry has invaded), P_s is the pressure of the fluid in seal area between the plunger and the top cap. Before the sampler is lowered into the trench P_s will be equal to atmospheric pressure (if P_s were less than P_i the plunger would be pushed up against the top cap by the pressure differential). As the sampler is lowered into the trench P_s is likely to increase above P_i as some fluid seeps in. Thus at best the second term in Equation 1 will be zero and if there is fluid seepage it will be negative

I do not have dimensions of the sampler but from memory A_e and A_s might both be of order 30 cm². The effective weight W of the sampler tube in the slurry is unlikely to exceed about 10 kg. Thus the maximum depth in the slurry before it begins to invade the sampler will be of order 3 m if the slurry does not penetrate the seal area (from inspection of the seal it seems very likely that this will occur) and thus invasion may start at an immersion depth of less than 3 m.

If slurry seeps into the sampler, before the plunger is released, it is possible that some air will remain trapped within it. If none of the air escaped then from Boyle's law the volume of air in the sampler would be halved when the external slurry pressure reached 1 bar that is at a depth of order 9 m. It follows that the slurry in the sampler, when withdrawn, may be from a range of depths (starting at about 3 m) and that the contribution from any depth will depend on the air compression and air escape and thus will be indeterminate.



Schematic diagram of Sampling Device

Figure A1

Sampler

| | | | |
|------------------|--|------------|------------------|
| Overall diameter | | 0.12 | m |
| Area | | 0.01131 | m ² |
| Length | | 0.4 | m |
| Vol | | 0.004524 | m ³ |
| Upthrust | | 4.523893 | kg |
| | | | |
| Plunger | | | |
| Overall diameter | | 8.89 | cm |
| Outer diameter | | 6.35 | cm |
| Overall area | | 62.07167 | cm ² |
| Outer area | | 30 | cm ² |
| Seal area | | 30 | |
| | | | |
| W | | 98.1 | N |
| As | | 0.003 | m ² |
| Ae | | 0.003 | m ² |
| Pi | | 1.00E + 05 | N/m ² |
| As Pi | | 300 | N |
| Unit wt | | 10791 | N/m ³ |
| d | | 3.030303 | |
| | | | |
| | | | |
| If invaded | | | |
| As/Ae + 1 | | 2 | |
| W/gs/Ae | | 3.030303 | |
| d | | 1.515152 | |