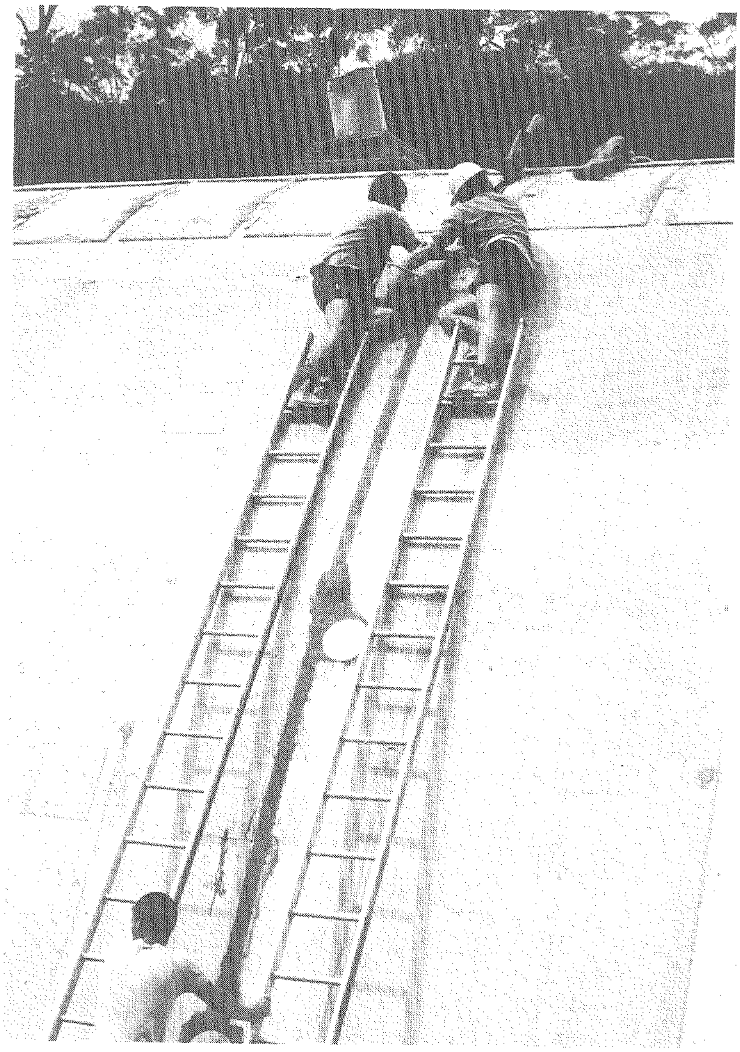
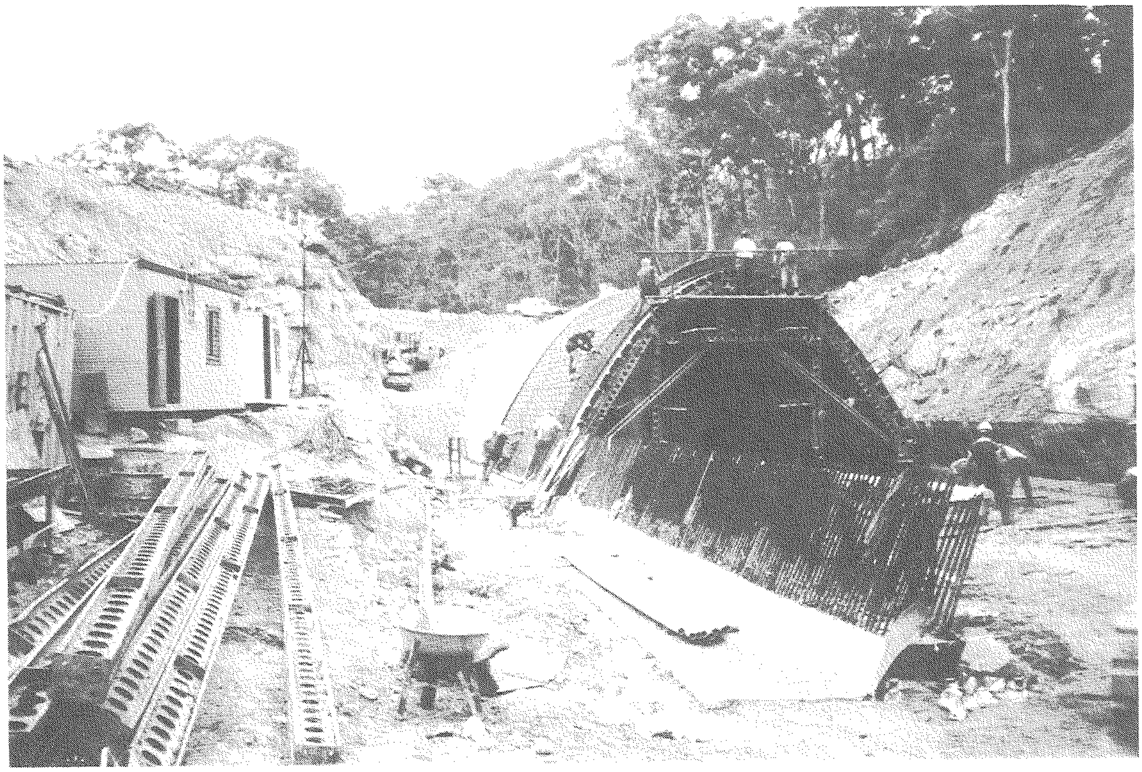
View showing the upper earth pressure cells being grouted into place

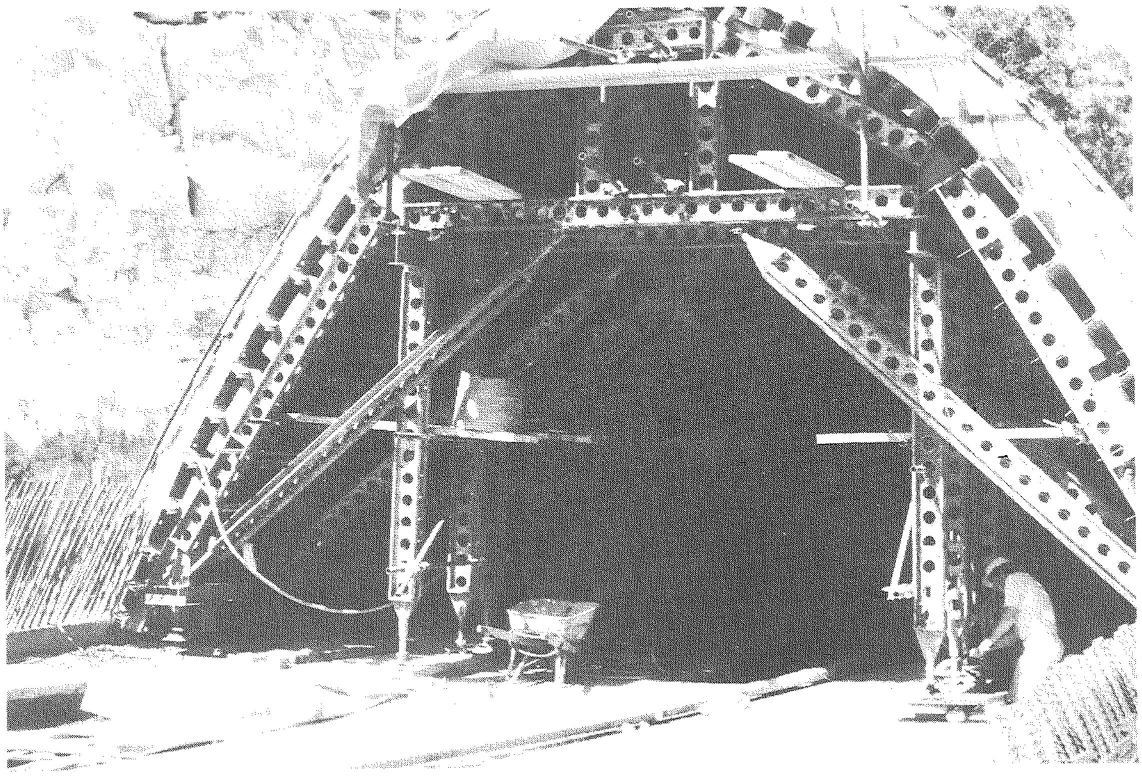


View showing reinforcement and size of culvert

Work being carried out on the 5.5 m high culvert on the F3 Freeway, Wahroonga, NSW



View of culvert showing inner form details and tight left hand valley side.



View showing inner form

Construction work being carried out on the culvert used for one of the prediction exercises.

PREDICTION OF EARTH PRESSURES ON CULVERT, F3 FREEWAY, WAHROONGA, NSW

G. Mostyn
B. De Wit
B. Knoop
J. Small
M. Kurzeme

SUMMARY This paper presents a summary of the methods adopted and predictions obtained by various engineers of the earth pressures measured about a large rigid culvert under relatively deep compacted fill. The methods adopted vary from simple earth pressure theory to numerical stress analysis. The various predictions are compared with the stresses measured from earth pressure cells embedded in the outer face of the culvert.

1.0 INTRODUCTION

The Department of Main Roads, N.S.W., is currently improving many main roads around Sydney. Substantial new work is being undertaken on the F3 Freeway connecting Sydney to Newcastle. One section of the F3 Freeway extends northwards from Wahroonga to Berowra, to the north of Sydney, and crosses several creeks. These crossings involve the construction of rigid reinforced concrete parabolic culverts of 3.5 and 5.5m height under compacted fill of up to 30m depth. The gullies in which the culverts run are often quite asymmetrical; one side is in cut and is very steep or tight and the other side is much flatter or open. The structural design of the culverts has been based on empirical methods and is thought to be quite conservative.

Several other large culverts will be required in the next decade and the Department therefore decided to instrument two culverts and monitor the actual pressures on the outside of each. These results will be compared with those obtained by several different methods of prediction and hopefully result in more economical design of any future culverts.

As part of the Prediction sessions at the Fifth Australia-New Zealand Geomechanics Conference in Sydney in August 1988, participants were requested to predict the pressures on one of these culverts.

Filling over the first (and smaller) of these culverts was completed prior to the conference and each predictor was requested to predict the pressures measured about this culvert. It should be noted that as in most geotechnical problems not all the information that may have been desired was available to the predictors.

The following sections present the information that was made available to the predictors; the methodology adopted by each predictor; and finally a comparison of the predicted and actual performance.

2.0 THE PROJECT AND PREDICTION REQUESTED

2.1 SITE TOPOGRAPHY

The subject culvert is located just to the east of Hornsby, approximately 20 km north of Sydney, and is sited in the base of a relatively deeply incised and steep sided gully cut down into Hawkesbury Sandstone. Approximate original surface contours are shown on the plan of the culvert on Figure 1 and a more detailed cross section of the stripped surface at the instrumented section is included on Figure 2. As can be seen, and is typical of slopes in this sandstone, the natural surface contains terraces separated by steep slopes.

2.2 GEOLOGICAL SETTING

As this is primarily an above ground construction only brief details of the geology are given; further information on the Hawkesbury Sandstone and Sydney Basin are readily available in the literature, if required.

The culvert and overlying embankment fill are sited over Hawkesbury Sandstone bedrock. This is a quartz rich sandstone with clay cement and quartz overgrowths and has bedding thicknesses typically of 1 to 2m; individual beds are either cross bedded or massive. Strength varies typically from 15 to 40 MPa.

At the culvert the sandstone was overlain by a poorly developed topsoil and a thin layer of colluvium formed by insitu weathering and downslope movement of sandstone blocks. All soil was stripped prior to construction of the culvert or placement of embankment fill.

2.3 PHYSICAL LAYOUT OF THE CASE STUDY

The culvert is 3.5m high and approximately 180m long and is shown in longitudinal section and plan on Figure 1. A cross section of the gully normal to the culvert

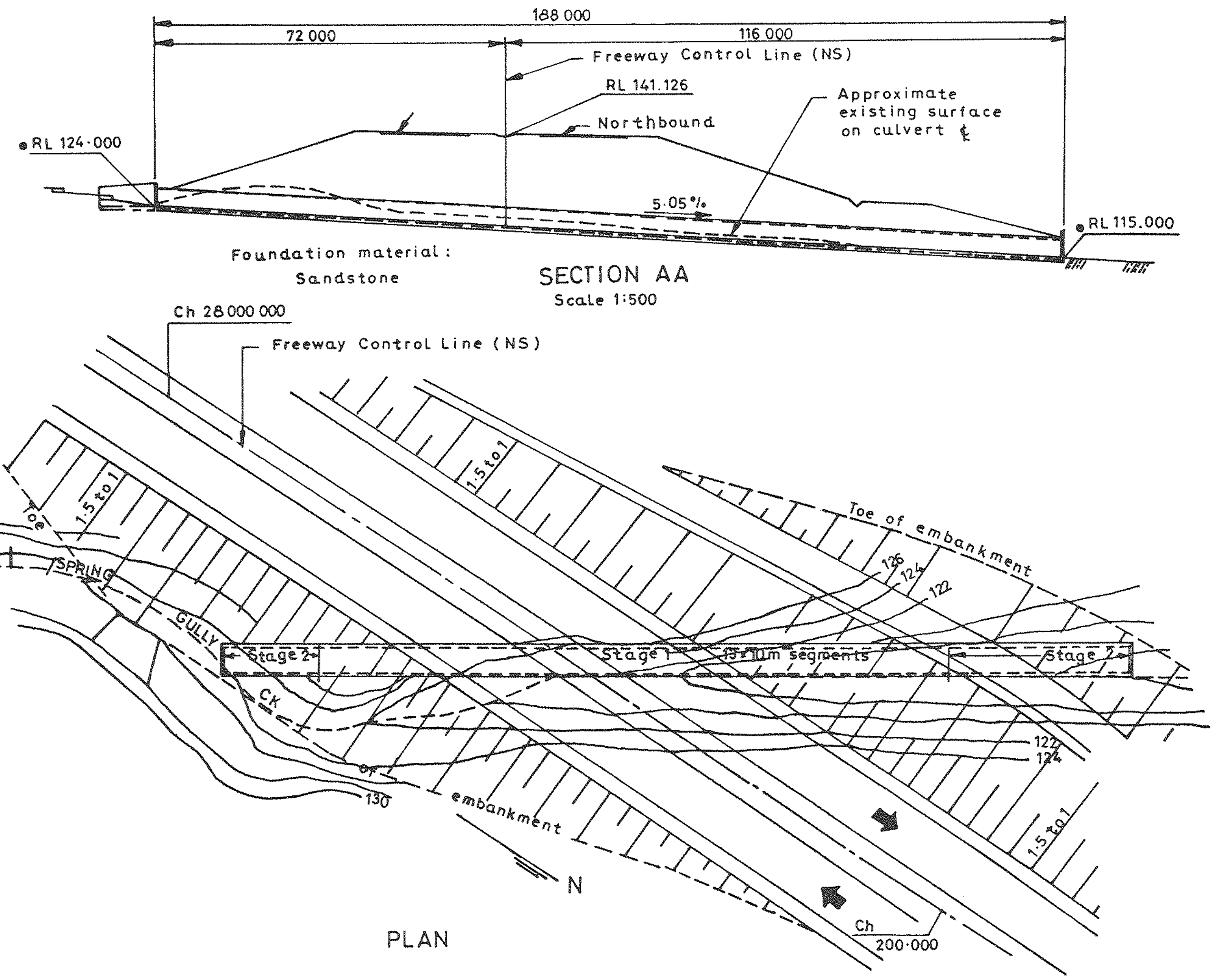


Figure 1 Plan and longitudinal section of culvert

axis at the instrumented section is included on Figure 2, this also shows the final embankment at this section. Figure 3 includes a larger scale cross section of the culvert itself showing the locations of the ten earth pressure cells (numbered 51 to 60) which were installed to be flush with the outer face of the concrete culvert. Note that cells 52/53 and 58/59 are redundant pairs of cells at the same level on the culvert. The steep (tight) side of the gully is on the south side of the culvert.

2.4 SITE INVESTIGATION INFORMATION

Very little site investigation was undertaken for the culvert itself. Most of the relevant information has been obtained during construction and is discussed in the next section.

2.5 CONSTRUCTION DETAILS

Briefly, the construction sequence was as follows:

* The entire foundation area for the embankment was stripped of soil and any overhanging sandstone ledges removed.

* The foundations for the culvert arches were prepared and poured.

* The culvert itself was constructed in intermittent panels.

* The instrumentation was installed and a metre of clean uniform medium grain sized sand placed around the earth presssure cells for protection.

* Ripped and blasted sandstone fill was placed to near the final embankment level. The specification for the fill allowed a layer depth of up to 450 mm with a maximum particle size of up to two thirds of the layer depth. In accordance with the DMR specification the fill was to be compacted to 95% of maximum dry density (standard compaction) at 60 to 90 percent of optimum moisture content. Some of the fill was quite clayey and the specification was changed to 98% of maximum dry density (standard compaction) at up to optimum moisture content.

* Initially the fill was raised at different rates on the north and south sides of the culvert. The levels of the fill versus time are given on Figure 4. Routine earthworks control included insitu density tests; the results of those tests completed within the fill overlying the culvert indicated a mean total density of 2.05 t/m^3 with a

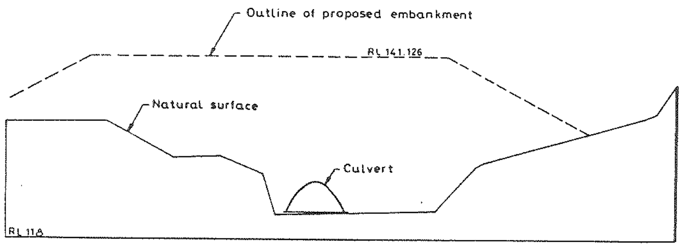


Figure 2 Cross section of embankment and culvert

standard deviation of 0.07 t/m^3 and a mean moisture content of 12.1% with a standard deviation of 4.6%. The dry density of the fill decreased and the moisture content increased as the filling proceeded. The above information on the filling was given in more detailed form to the predictors.

* The earth pressure cells were monitored during this period.

2.6 INSTRUMENTATION DETAILS

Three different types of instruments were used to monitor the stresses on and within the culvert. Twenty strain gauges were attached to the transverse reinforcing steel within the concrete; the strains indicated by these were measured during each monitoring cycle. Seven reference eyes were installed around the inside face of the culvert; a tape extensometer was used to accurately record any differential movement between these. These two systems enable the deformation and, therefore, stresses within the culvert to be determined.

Finally, and of most interest to this prediction, ten earth pressure cells were installed around the outside face of the culvert. These were installed normal to and flush with the face with the leads run through a block out in the crown of the culvert.

2.7 PREDICTIONS REQUIRED

The participants were requested to predict the readings obtained from the 10 earth pressure cells that had been installed and monitored on the smaller culvert. The resulting predictions were to be presented in two forms:

(a) The earth pressures measured near the end of construction (i.e. on the 6th April 1988) should be provided in the following format.

Earth pressures (in kPa) at the 6th April 1988:

Cell number	51	52/53	54	55
Earth pressure				
Cell number	60	59/59	57	56
Earth pressure				

(b) The earth pressures (kPa) versus time (in days from the 10th September 1987). A standard form of graph was requested.

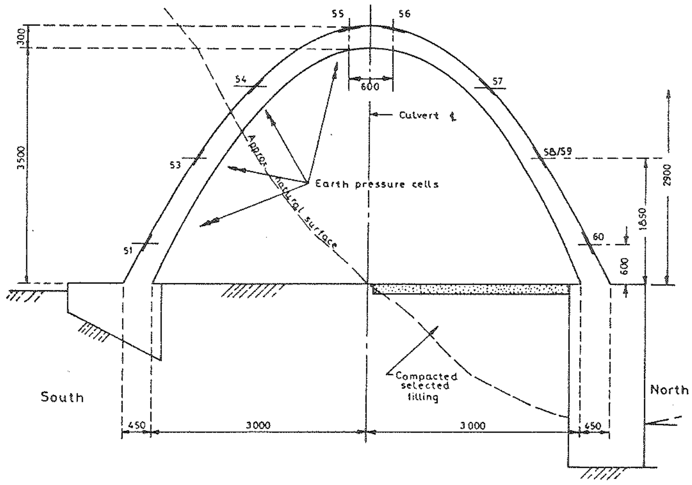


Figure 3 Cross section of culvert showing locations of earth pressure cells

3.0 BEN DE WIT PREDICTION

This prediction was obtained from work completed as part of a Master of Engineering Science project which involved a literature search for simplified design methods and numerical analyses of the culvert (De Wit, 1988). As this analysis was completed in December 1987 the results of the monitoring were not available; thus this prediction is based on the same information as that available to the other predictors.

3.1 Methods of Analysis

Two different methods of numerical analyses were adopted: (i) a finite element analysis (SUPERSAP) and (ii) a finite difference analysis (FLAC). The programmes to impliment both methods are able to run on commonly available microcomputers.

SUPERSAP

Supersap is a finite element analyses adapted for use on microcomputers from the larger SAP package available on mini-computers and mainframe computers. The program analyses a model which consists of a grid of 2 dimensional rectangular elastic

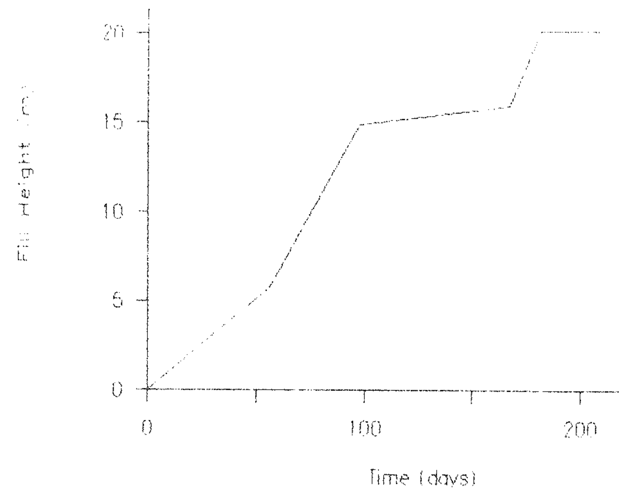


Figure 4 Height of fill versus time

soil and culvert elements or 3 dimensional beam culvert elements. Incremental fill height analyses were not undertaken although this can be done with some additional file manipulations.

FLAC

This analysis simulates the behaviour of structures, built of elastic or non-linear materials, which undergo plastic flow when their yield limit is reached. FLAC is a dynamic analysis which solves problems by stepping the model through time, allowing kinetic energy to be damped out. Approximate static solutions of stress and displacement are obtained when velocities are less than a specified cut-off.

The model consists of a grid which has been generated and deformed to represent a particular geometry and the delineated discrete elements are assigned material properties. The analysis allowed stress and displacement determinations after each addition of consecutive fill layers up to full depth. Compaction was simulated by temporary surcharges.

3.2 Material Properties

The fill was treated as an elasto-plastic Mohr Coulomb material in the FLAC analysis and as an elastic material in the SUPERSAP analysis.

Material properties were not accurately known but were assumed on the basis of limited experience with similar materials, the following values were adopted:

Density	19 kN/m^3
Poisson's ratio	0.35
Cohesion	0
Friction angle	35 degrees
Secant modulus	30 - 350 MPa

The soil modulus was set according to a predetermined linear relationship with fill height.

The culvert was treated as an elastic material with the following properties:

Density	24 kN/m^3
Poisson's ratio	0.2
Young's modulus	33 GPa

The culvert foundations and valley floor were assumed to be rigid. No slip was allowed between the culvert and fill or between the valley floor and the fill.

3.3 Discussion

The results of the analyses are given on Table I and Figures 10 & 11 and are discussed later in this paper.

4.0 BRAM KNOOP PREDICTION

The following procedures were adopted to predict the earth pressures on the culvert.

* An assessment was made of the information provided in the package, including fill height and density, culvert shape and instrument locations, excavation shape and compaction.

* Other factors included the time available to complete the prediction, and the availability of computing facilities and reference material. Only a few evenings were available and all available computing facilities were being utilised on work related projects. Thus numerical analysis was precluded but HEC data included fill pressure observations on the diversion conduit at the Parangana Dam in 1967-68.

* These observations had been obtained with Glotzl pressure gauge equipment. Fourteen gauges had been installed with orientations varying from horizontal to vertical. The embankment fill consisted of a glacial till core and rockfill shoulders and ranged in density from 21 to 22 kN/m^3, i.e. similar to that in the highway embankment.

* The observations at Parangana Dam indicated high pressures on the top of the culvert and progressively lower pressures on the 45 degree chamfers and near vertical sides. It was also found that the pressures did not increase linearly with fill height. These observations are thought to be related to: stress concentration due to the rigidity of the culvert; compaction effects; and low horizontal stresses.

* The compaction effect was estimated at being equivalent to approximately 1 metre of fill, i.e. 20 kPa. This led to comparisons between observed gauge pressures and overburden stress plus 20 kPa expressed as the ratio R and shown on Figure 5. These plots indicate two fairly distinct ranges of linearity.

* The information on Figure 5 was used to interpolate R values for the highway culvert taking account of the gauge orientations and fill height.

* The insitu density data provided indicated a slight decrease in density (from 2.06 to 2.02 t/m^3), and increase in moisture content, for the fill placed above 4m height, this variation in total density was used in determining the overburden pressure.

* The interpolated R values and overburden pressures were used to predict the guage pressures versus time. Slightly lower values of R were adopted for gauges on the cut side of the culvert.

* The predicted fill pressures are shown on Table I and Figures 10 & 11 and are discussed later in this paper.

5.0 JOHN SMALL PREDICTION

In order to obtain a quick solution to the culvert problem which has been outlined in the previous sections, a routine finite element analysis was used. This method was chosen because it was thought to be able to model the effects of the open and tight

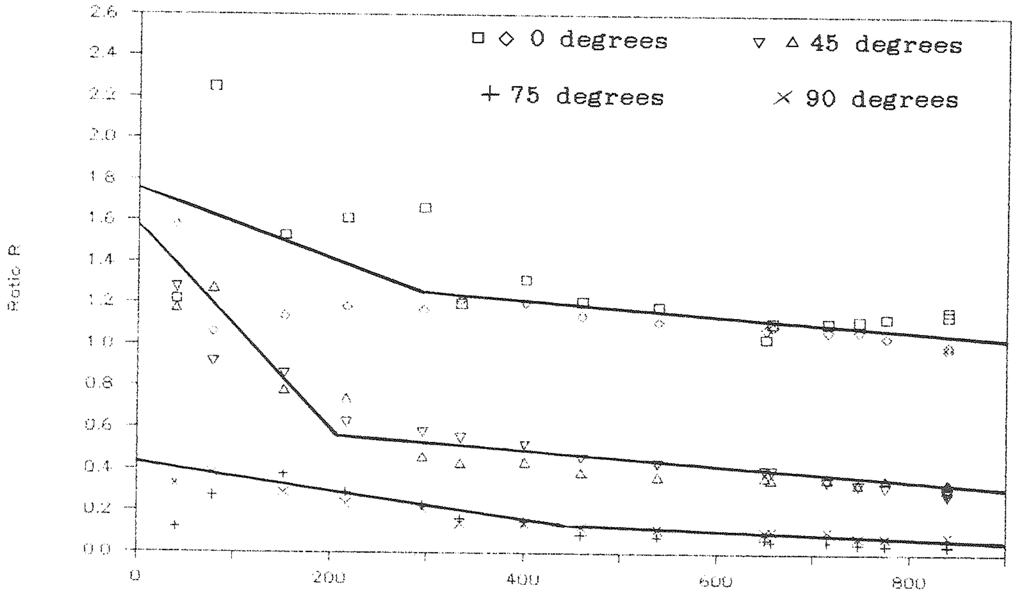


Figure 5 Parangana Dam culvert pressures

sides of the gully.

The finite element mesh that was used is shown on Figure 6 where it may be seen that elements were arranged in horizontal rows so that the placement of the fill above the culvert could be modelled. Pressures on the sides of the culvert, which were to be predicted, were obtained from the stresses calculated in the elements next to the culvert.

As very little data of the type that is needed for a finite element analysis was made available, many assumptions and simplifications had to be made. Many refinements which could have been made in the analysis were omitted because of the short amount of time available to make the prediction, and it is therefore not known whether these were significant.

The following sections present a description of the method of analysis, the assumptions made and the deficiencies in the analysis. The results are presented, discussed and compared with measurements later in this paper.

5.1 Assumptions Made and Deficiencies in Analysis

In carrying out the finite element analysis the culvert itself was treated as being stiff and assumed to behave in an elastic fashion. This would not be true if the culvert were of the thin flexible steel type, however as it was constructed of concrete approximately 500 mm thick this was thought to be a fair assumption. Other simplifying assumptions made in the analysis are listed below:

* The soil placed above and around the culvert was linear and elastic.
* No slip was allowed between the culvert and the soil.
* Simple triangular elements were used.
* The mesh was fairly coarse in the region of the culvert.
* No allowance was made for compaction stresses.
* Stiffening of the fill with increasing stress was not considered.

5.2 Method of Analysis

In order to simulate the construction process, the full finite element mesh was generated and self weight was applied to each horizontal layer of elements in turn. The process of adding fill was modelled by "turning on" the weight of each layer of elements representing the soil. Any elements which were not required (i.e. those representing fill which had not yet been placed) were assigned zero modulus so that they had effectively no stiffness and were not included in the analysis. All elements within the concrete culvert were also given zero modulus.

This method of analysis may not be the most efficient but has the advantage that a single rectangular mesh may be generated quite simply and the analysis does not involve adding more elements to the mesh as construction proceeds. Although the actual fill was placed in much thinner layers than in the simulation, it has been shown that this does not lead to significant errors.

Stresses measured by the stress cells were calculated from elements in the soil next to the culvert. The stresses normal to the culvert had to be computed as these should be the stresses measured by the cells.

The position of the natural rock surface was only approximated at either side of the valley as the elements in the finite element mesh did not exactly coincide with the true surface. However the surface approximation was thought to be close enough to the true surface not to introduce large errors.

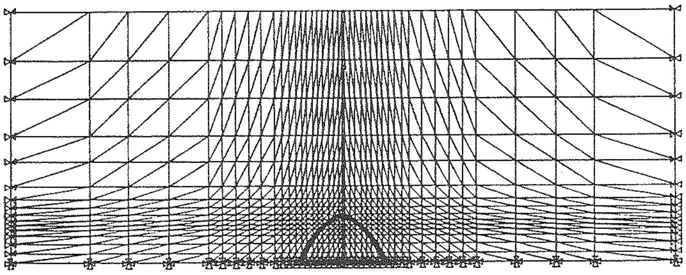


Figure 6 Finite element mesh showing position of culvert

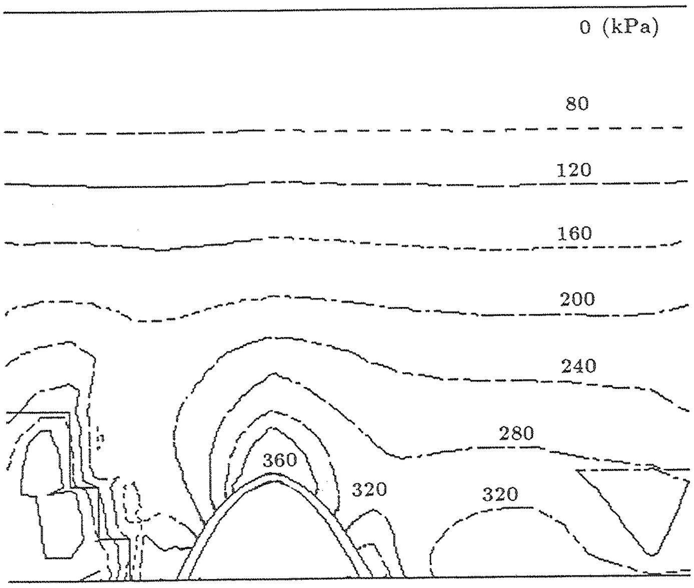


Figure 7 Predicted vertical stress contours for fill at final level

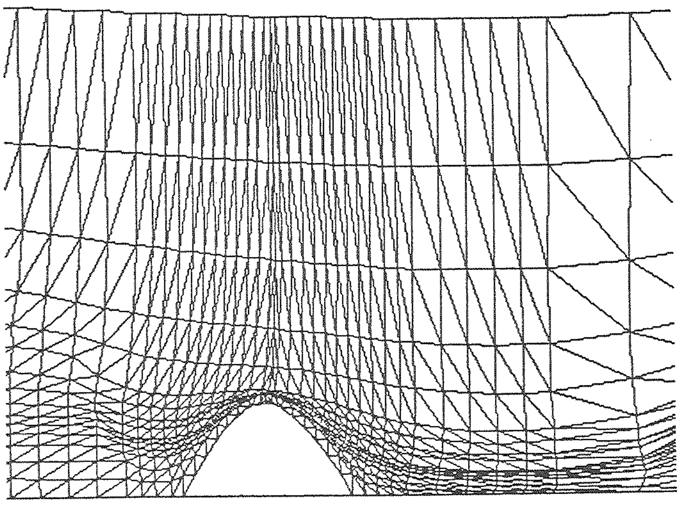


Figure 8 Deformed mesh showing compression of fill under self weight at exaggerated scale

5.3 Results of Analysis

The results of the analysis are given on Table I and on Figures 10 & 11 and will be compared with measured pressures later in this paper.

The principal stress information for when the fill has reached the top of the culvert indicates that there are large stresses in the culvert itself and that away from the culvert the principal stresses are vertical and horizontal.

The contours of vertical stress when the filling is complete are shown on Figure 7, these indicate that the vertical stresses directly above the culvert are much higher than those which would be expected from the 16.5m of overburden which exists at this stage. This is due to the fact that the fill on either side of the culvert is settling more than the fill overlying the culvert, this is readily seen on Figure 8 showing the deformed mesh.

When the culvert is close to the gully wall (the left hand side of the diagrams) vertical stresses are lower due to the arching action of the fill as was anticipated before the analysis.

It should be pointed out finally, that although the material properties of the fill were not known, this would not be expected to seriously affect the results since stresses only were to be predicted. As long as the relative magnitudes of the various moduli are correct and the Poisson's ratios chosen are realistic, the elastic analysis should yield reasonable results. If settlements of the fill were required, realistic choices of material properties be essential.

6.0 MARCUS KURZEME PREDICTION

6.1 Approach Adopted

The effect of compaction on the horizontal stresses was estimated following Ingold (1978) which indicated that these stresses in the near surface region were related to the weight of the roller used in compaction. A coefficient of lateral earth pressure (k) of 0.5 was "estimated" for the fill; this value was really a guess and is the most important parameter in the entire prediction approach. Assuming that the roller weighed 80 kN/m implied that the effects of compaction were felt up to 3.2m below the surface. Beyond this depth the horizontal stress was taken to be k times the vertical stress.

The vertical stress was taken to be the overburden pressure due to self weight of the fill alone. The horizontal and vertical stresses were used to determine the normal stress at each pressure cell location. The prediction is presented in Table I and on Figures 10 & 11 and is discussed later in this paper.

6.2 Comments

The following comments are offered:

* The roller weight was guessed as no information was provided.

* The prediction required was for the readings on the pressure cells and this may differ from the actual earth pressures on the culvert.

* Very little is really known about the materials involved.

* The size and stiffness of the earth

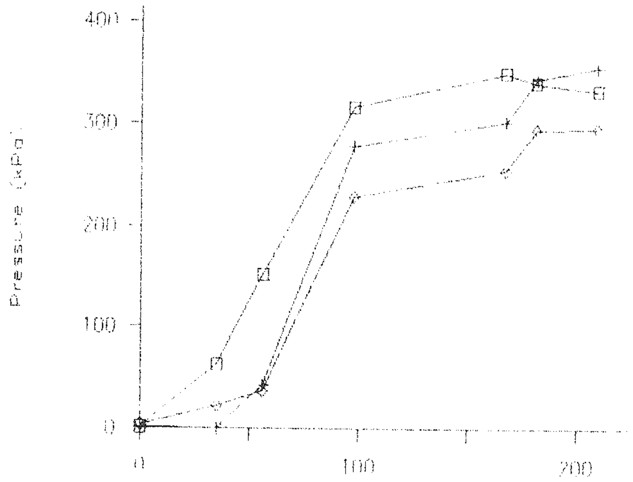


Figure 9 Measured culvert pressures versus time

pressure cells was not given.

* The approach adopted did not include any allowance for the effects of arching due to the steep abutment, to include this would have been adding a straight guess.

* For the approach adopted the important final readings depends only on the estimate of k and thus the exercise can be used to predict a reasonable value of k.

7.0 MEASURED PRESSURES

(a) Earth pressures (in kPa) measured on the 6th April 1988 were:

Cell number	51	52/53	54	55
Earth pressure	49	337/329	91??	295
Cell number	60	59/59	57	56
Earth pressure	689??	300/293	344	416

(b) The results for three pairs of cells are shown on Figure 9. These pairs have been selected to eliminate some of the noise from the measured values. Pair 55/56 represent the pressure on the crown of the culvert. Pairs 52/53 and 58/59 represent the tight and open side of the culvert respectively.

7.1 Discussion of Measured Values

The pressures measured on the 6th April 1988 in general are consistent with those measured as the filling progressed. The readings at Cells 54 and 60 appear anomalous and may not reflect the true pressures on the culvert; alternately it is possible that they accurately indicate the presence of localised "hard" and "soft" spots in the fill. The very high reading at Cell 60 was consistently recorded from the start of filling and possibly is due to very high locked in horizontal stresses just above the rigid footing.

The actual recorded readings for the redundant pair 58/59 were always within a few percent of each other; while those for the pair 52/53 had a maximum difference of about 20 percent but generally were about 10 percent apart. These differences probably indicate that high pressure gradients are possible in a variable fill like ripped sandstone.

In general the pressures appear to be somewhat lower on the tight side (i.e. cells 51-55) of the culvert than on the open side (i.e. cells 56-60). Unfortunately this observation is not reflected in the redundant cell pairs adopted for the overall comparison of the predictions. At best it could be said that the information available from this culvert does not alone provide strong evidence for reductions in pressures on culverts in asymmetrical valleys.

8.0 COMPARISON OF PREDICTIONS WITH PERFORMANCE

8.1 General Comparison

The predicted earth pressures on the 6th April 1988 are given on Table I. The difference between the measured and predicted culvert pressures for selected pairs of cells is plotted versus time for each predictor on Figure 10. Predicted versus measured pressures are plotted on Figure 11.

The following points can be noted by reference to Table I:

* It can be seen that none of the methods predicted the pressures on the lowest cells at all well. Cell 51 was substantially over estimated by all procedures except De Wit's FLAC analysis, which gave a substantial under estimate. The measured pressure on Cell 60 was far greater than any estimate. This discrepancy requires further investigation.

* If Cells 55 and 56 are taken to represent

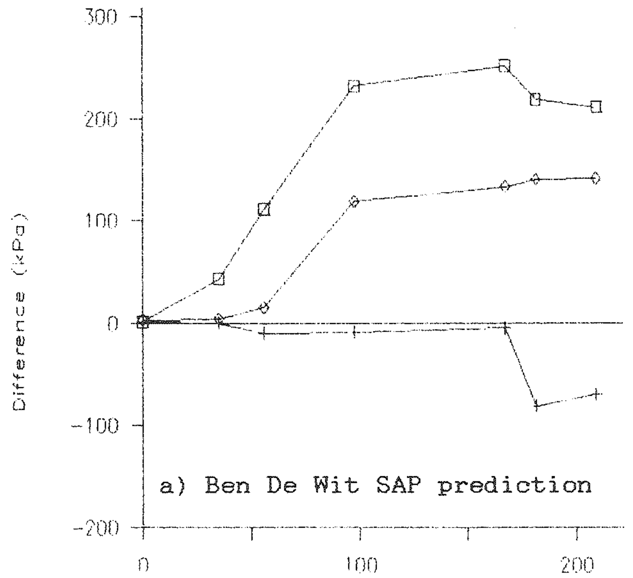
TABLE I
PREDICTED AND MEASURED EARTH PRESSURES
AT 6th APRIL 1988

	Cell Number							
	51	52/53	54	55	56	57	58/59	60
De Wit SAP	120	120	250	420	425	250	150	210
De Wit FLAC	10	170	325	400	400	250	250	210
Bram Knoop	115	130	160	395	410	180	250	210
John Small	105	170	240	480	490	275	135	120
Mark Kurzeme	355	345	355	350	350	355	345	355
Measured	49	337/329	91??	295	416	344	300/293	689??

the pressure on the crown of the culvert then all the methods reasonably predicted these, see also Figure 11 (b). These pressures were least well predicted by the FEM approach of John Small probably because the relative stiffness of the soil allowed too much arching and thus resulted in higher pressures on the crown. Mark Kurzeme's prediction which ignored any arching effects was the only method not to over estimate the crown pressure.

* The measurements for pairs 52/53 and 58/59 are almost the same and are higher than all predictions except that of Mark Kurzeme, see also Figure 11. The other predictions included too much arching or effects due to asymmetry which was not apparent in the observed pressures.

* The pressures on Cell 54 was generally over estimated and on Cell 57 under-estimated.



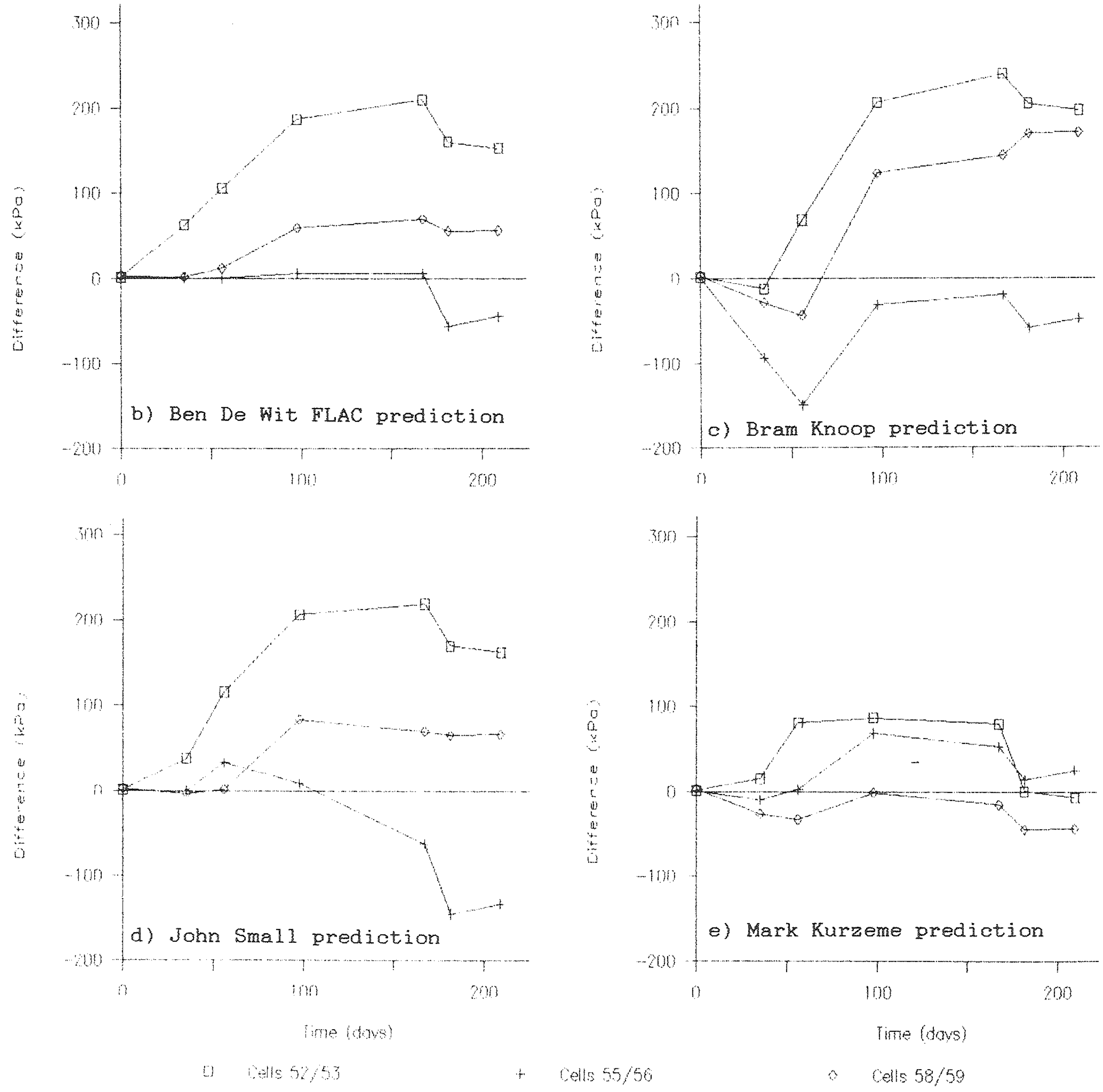


Figure 10 Difference between measured and predicted culvert pressures

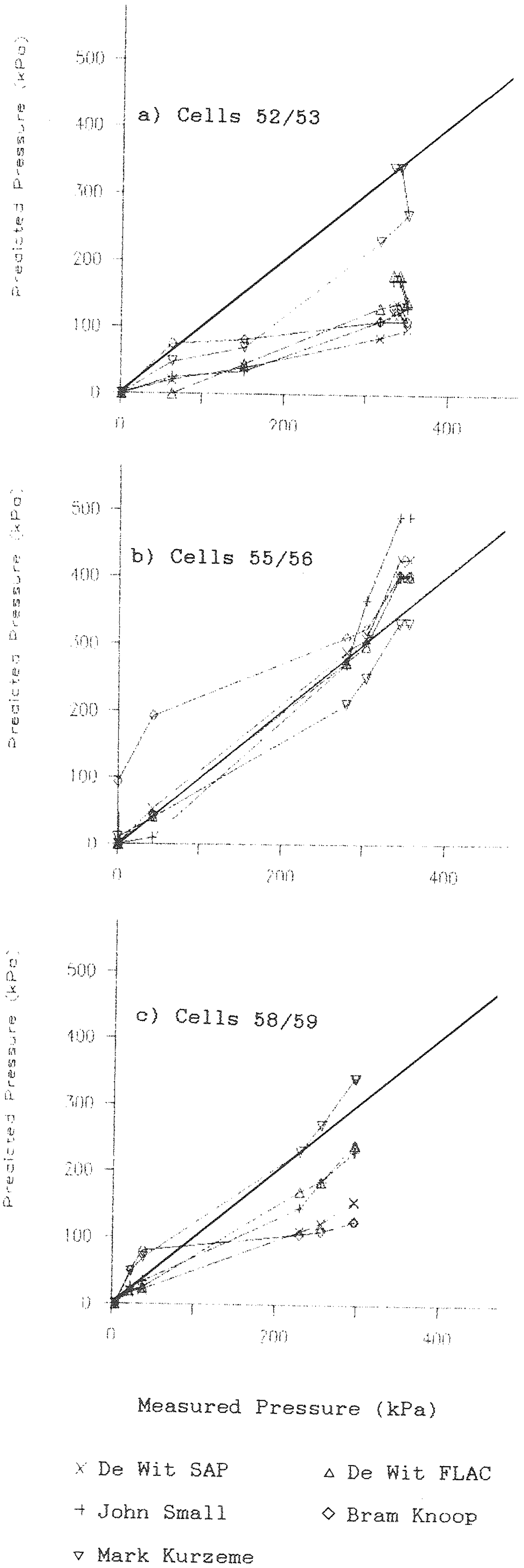


Figure 11 Measured versus predicted culvert pressures

* While most of the predictions resulted in a relatively smooth variation in stress about the culvert, the measured pressures vary quite erratically. This makes detailed analysis of the results difficult.

The following can be determined by reference to Figure 10:

* Ben De Wit's prediction of crown pressures were very accurate till about 160 days and then wandered from the observations.

* Except for Mark Kurzeme the side pressures (Pairs 52/53 & 58/59) were always under estimated.

* Mark Kurzeme's prediction is the most accurate for the three pairs of cells analysed. The other methods generally under estimated some of the measured pressures by fifty percent.

The more sophisticated methods did not predict the side pressures very well but did predict the crown pressures reasonably, this may be due the the fact that by and large these methods ignored the possibility of high locked in horizontal stresses due to compaction. These could generate large pressures on the side of the culvert but would be unlikely to effect the crown pressure.

Out of interest the pressures that would have existed on the 6th April 1988 at the three pairs of cells shown in Figures 10 & 11 were computed considering only the vertical overburden pressure, a coefficient of lateral earth pressure (k) and the inclination of the surface under consideration (i.e. from simple statics). Thus the effects of the culvert and asymmetry were ignored. When k was in the range 0.5 to 1.0 this calculation indicated pressures very close to those actually measured. This would be expected for a Type C prediction of this nature. The best fit was for k equal to 0.7. This provides some support for the use of a coefficient of lateral earth pressure of 0.7 in similar compacted fills. This value should be confirmed by analysis of the results of the other culvert and of any other information available (e.g. Parangana Dam).

It is important to remember that the predictions reported above were generally completed in a short time and generally without the benefit of some relatively important input parameters. Thus the accuracy of the results should not be used to assess the relative merits of the various methods employed. The results are presented purely for information purposes and should be used with this in mind.

9.0 ACKNOWLEDGEMENTS

The conference orgainising committee would like of acknowledge the Department of Main Roads, NSW (now the Road and Transport Authority) for allowing this information to

be used for one of the case study predictions at the Geomechanics Conference. In addition Linsay O'Keefe collected and collated most of the actual performance information and his willing assistance is gratefully acknowledged. Harry Wong assisted John Small in generating the mesh adopted in his prediction and this assistance is gratefully acknowledged.

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