NON-LINEAR ANALYSIS OF BURIED ARCH STRUCTURES

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SUMMARY

Groupe TAI introduced the TechSpan™ arch system in 1986. Since then over 500 buried precast concrete arches have been completed to site specific designs using a design method based on finite element analysis.

In order to verify the design system the finite element analysis results have been compared with alternative analysis methods and with measurements of actual structures during construction. In an earlier paper the finite element results were compared with alternative simplified design methods. In this paper the results of different finite element analyses are compared, and these results are compared with further site measurements.

The focus of this paper is to investigate the effect on the analysis of the assumed construction sequence and the use of non-linear materials properties. The following analyses were carried out:

- Standard TechSpan design procedure; ie Non-linear soil properties; elastic concrete properties; staged soil loading.
- Non-linear soil and concrete properties; staged soil loading
- Elastic soil and concrete properties; soil loading applied in one stage
- Non-linear soil and elastic concrete properties; soil loading applied in one stage

The modelling of the loading sequence was found to have a significant effect on the results, with the single stage analyses giving poor correlation with site measurements and the other analyses. The results of the standard analysis carried out for TechSpan design was found to be in excellent agreement with the site measurements, and predicted reinforcement stresses were found to be slightly conservative. The use of non-linear concrete properties gave results very close to the elastic analysis, and also in excellent agreement with the site measurements.

1 INTRODUCTION

1.1 The TechSpan™ Arch System

The TechSpan™ system consists of a two piece, three pin, buried precast concrete arch, usually constructed with Reinforced Earth™ head walls and wing walls (Figure 1). Arch dimensions are typically in the range of 5 to 20 metres span, and 3 to 8 metres height. Typical applications are road and rail crossings and tunnels and creek and small river crossings and diversions.

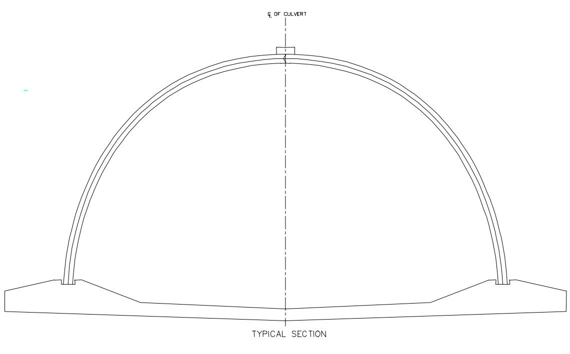

Figure 1; Typical Cross Section

Each arch is designed on a site specific basis, the arch profile being optimised to suit the needs of the client and to minimise forces in the completed structure.

1.2 The TechSpan Finite Element Analysis Method

A finite element analysis is carried out on every TechSpan arch, using our own software developed with the assistance of Prof. Ian Smith of the University of Manchester. Details of the programming techniques used are given in Smith and Griffiths [1]. The essential features embodied in the analysis are:

- An elasto-plastic soil model with soil stiffness and Poisson's ratio related to confining pressure.

- Soil loads are applied in stages reflecting the sequence of filling employed on site.

- A layer of "friction elements" is placed between the arch and the soil, allowing the soil to slip relative to the arch.

- A compaction load is applied to each backfill layer.

- The concrete is modelled as a linear elastic material.

1.3 Variations to the Analysis Method

An earlier paper by the author [2] compared the results of finite element analysis with alternative simplified methods of analysis and site measurements, and concluded that the finite element method gave superior results to the simplified methods.

The focus of this paper is to investigate the effect on the analysis of the assumed construction sequence and the use of non-linear materials properties. The following analyses were carried out using our in-house software, and the commercial finite element package "Strand6":

- Standard TechSpan design procedure; ie Non-linear soil properties; elastic concrete properties; staged soil loading.

- Non-linear soil and concrete properties; staged soil loading

- Elastic soil and concrete properties; soil loading applied in one stage

- Non-linear soil properties and elastic concrete properties; soil loading applied in one stage

1.4 Site Measurements

Measurements of deflections, soil pressures, and steel stresses have been taken at several sites in Japan. This paper compares in detail the measurements taken at the Kouchi Expressway TechSpan Project with predicted values.

Deflection measurements are compared with the results of the four different analyses. In addition the results of the standard TechSpan analysis have been compared with soil pressures and reinforcement stresses measured on site.

2 THE STANDARD FINITE ELEMENT ANALYSIS

2.1 Finite Element Model

The finite element model for a typical arch is shown in Figure 2. Eight noded plain strain plate elements are used for both soil and concrete elements. Thin friction elements are provided around the arch, and hinge elements at the base and crown allow rotation.

The model is built up in stages reflecting the actual backfill sequence; starting with the arch and foundation alone, then adding soil elements to each side of the arch alternately. For each stage a compaction load is applied then removed, so that only "locked in" compaction stresses and strains are added in to the next stage of the analysis.

2.2 Materials Properties

The soil model is based on the hyperbolic model developed by Duncan and Chang [3]. The soil stiffness (Young's Modulus, E) and Poisson's Ratio, μ, are related to the confining pressure, σ_3, by the four "Duncan constants": K, n, K_b, and m:

Young's Modulus :	$E/P_a = K(\sigma_3/P_a)^n$	(1)
Poisson's Ratio:	$\mu = 0.5 - E/6B$	(2)
Where:	$B/P_a = K_b(\sigma_3/P_a)^m$	(3)

The value of these constants may be determined from triaxial testing, or typical values for compacted

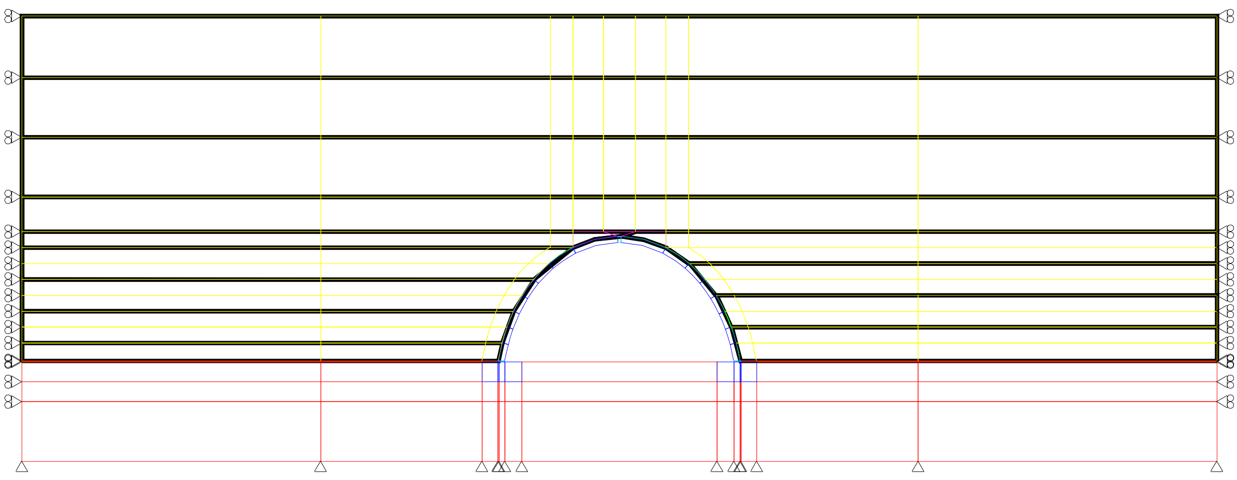

Figure 2: Finite Element Mesh

select fill may be assumed.

The soil parameters used in a standard TechSpan analysis for a typical select fill material are:

K = 500, Kb = 300, m = 0.2, n = 0.4

Hence for $\sigma_3 = P_a = 100$ kPa, E = 50 Mpa and $\mu = 0.22$

The soil failure stress is based on the Mohr - Coulomb criterion, using a friction angle of 30 degrees and no cohesion.

The concrete elements are assumed to be linear elastic in the standard analysis, with an E value of 20 GPa.

3 VARIATIONS ON THE FINITE ELEMENT ANALYSIS

The following variations were carried out to the standard procedure:

- The standard finite element analysis was repeated, but using non-linear concrete properties. The moment-curvature relationship for the reinforced concrete section under a range of axial loads is shown in Figure 3. In the analysis a variable effective E value was used, depending on the axial load and bending moment in the section as shown in Figure 4.

- The same structure was analysed using Strand6, with the soil loading applied in one stage. Separate analyses were carried out with linear and non-linear soil properties. Soil elements properties are available in Strand6, based on the same Duncan and Chang model as used in our in-house software.

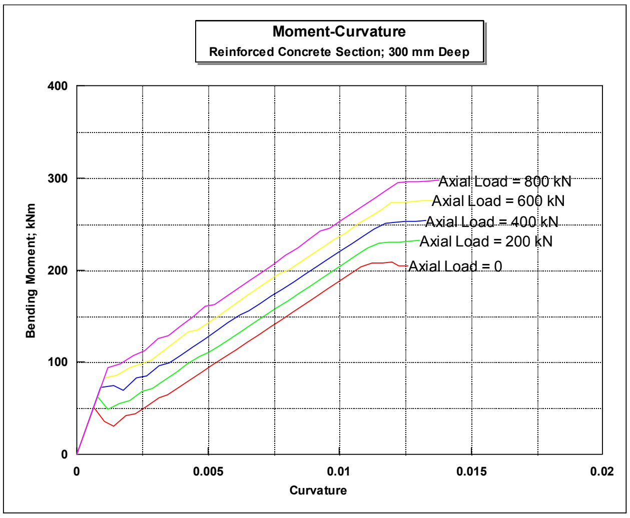

Figure 3; Moment Curvature Relationship

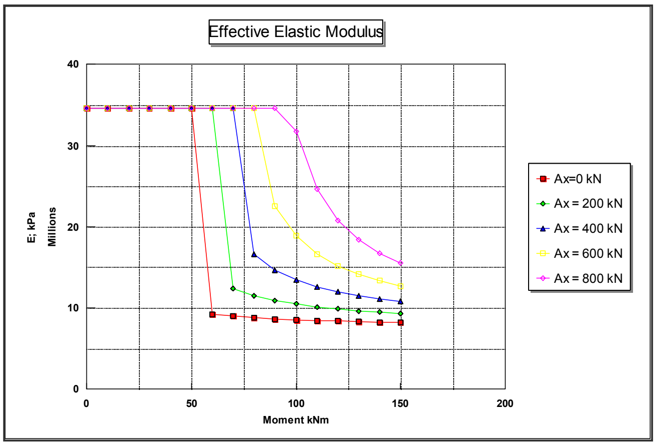

Figure 4; Effective Elastic modulus

4 SITE MEASUREMENT RESULTS

4.1 The Kouchi Expressway TechSpan

Deflection measurements were taken at the locations shown in Figure 5 at 9 cross sections. The average deflections from all nine sections have been plotted and compared with the analysis results. The horizontal deflections, DX1 to DX3, are the change in width at the indicated levels. The vertical deflections, DY1 and DY2, are the absolute change in level at the base of the arch, and the DY3 value is the vertical crown deflection relative to the base.

Reinforcement strains and soil pressures were also measured at each section.

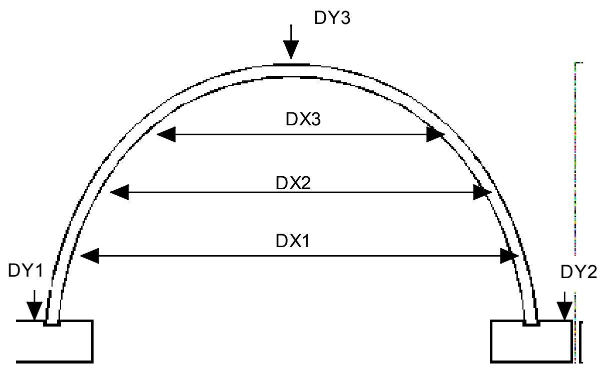

Figure 5: Location of Deflection Measurements

5 RESULTS OF THE ARCH ANALYSIS

For each set of analyses graphs have been plotted of:

- the change in arch width (DX1 to DX3), and the vertical deflection of the arch crown (DY3) against fill height (Figures 6-9)

- The envelope of maximum and minimum bending moments around the arch (Figures 10-12)

For the standard TechSpan analysis the following graphs have also been plotted:

- Reinforcement stress at the point of maximum bending moment (Figure 13)

- Maximum reinforcement stress plotted against vertical deflection at the arch crown (Figure 14)

- Vertical and horizontal soil pressures, and K value at the arch base, mid-height, and crown (Figures 15 – 17)

The corresponding site measurements are also included on these graphs where available.

6 DISCUSSION OF THE ANALYSIS RESULTS

6.1 The effect of staged loading

During the first stages of backfilling the soil pressure causes the arch crown to rise, and the sides of the arch to deflect inwards, as can be seen in Figures 6-9. In the case of the Kouchi arch inward and upward deflections of the order of 20 mm were measured when the fill was at the crown of the arch. As the fill height increases over the arch the increasing vertical pressure reverses the direction of the deflections, causing downward deflections at the crown, and horizontal bulging. The fill around the arch tends to confine these movements however, as the stress in the soil starts to move towards a passive state. When the soil loads are applied in the analysis in stages modelling the actual backfill sequence on site the analysis closely replicates the stress history in the actual structure, as can be seen from the close match between predicted and measured deflections.

Analysis in a single stage takes no account of the stress history in the soil however, resulting in predicted downward and outward deflections significantly higher than those measured on site. In this case the use of non-linear soil properties actually makes the situation worse, because the reduction in the soil stiffness acts in the same direction as the inaccuracies inherent in the single stage analysis. (See Figures 6-9, final deflections for the single stage analysis are indicated with arrows).

6.2 Non-linear versus elastic concrete properties

In the case of the Kouchi arch the use of linear elastic concrete properties has given results remarkably close to the non-linear analysis. The vertical deflections and change in width at three-quarters height are identical for practical purpose

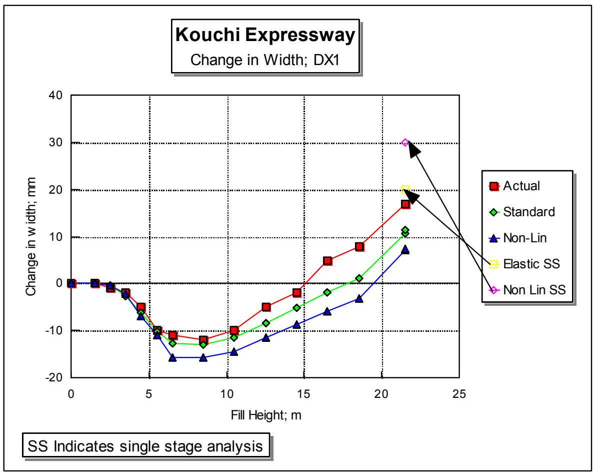

Figure 6; Change in width, ¼ height

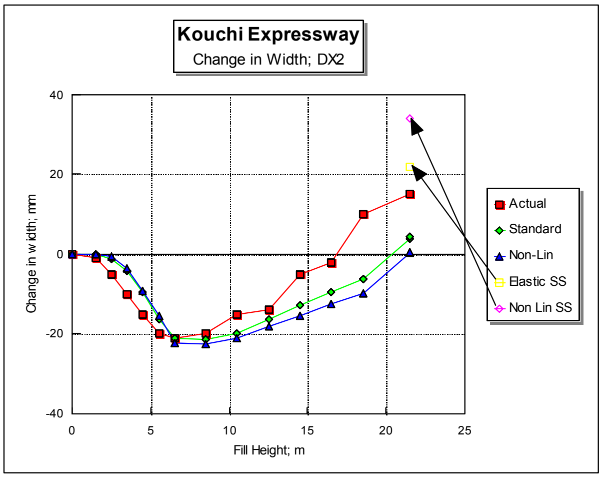

Figure 7; Change in width, mid height

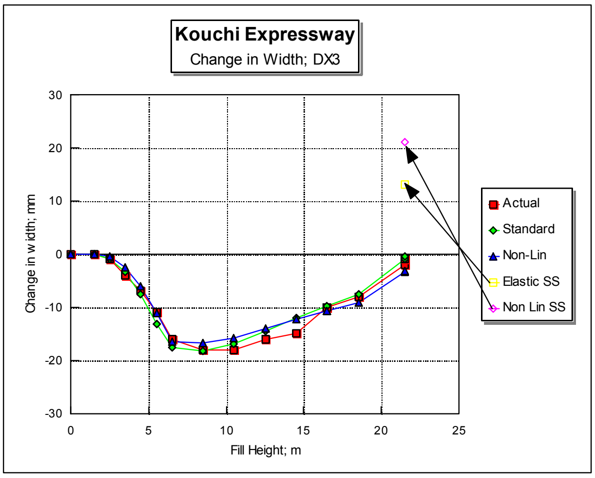

Figure 8; Change in width, ¾ height

(Figures 8,9). For the change in width at quarter height and mid height the elastic analysis actually gives results closer to the site measurements (Figures 6,7). The excellent results achieved by the elastic analysis are due to the use of a concrete stiffness value approximately midway between the uncracked value (35 Gpa) and the value for a fully cracked section (10 Gpa).

6.3 Bending Moments and Reinforcement Stresses

The bending moment envelope predicted by the two multi-stage analyses are shown in Figures 10 and 11. As would be expected from the close agreement of the deflections, the predicted moments are very close. The critical moment for design purposes is the maximum positive moment of approximately 100 kNm, which occurs when the backfill is at the crown of the arch, and the axial load is comparatively small. At completion of backfill the bending moment is greatly reduced, and the axial load is much higher, resulting in the tensile stress in the reinforcement being reduced to a very low level in the completed structure (see Figure 13).

The final bending moment diagram predicted by the two single stage analyses is shown in Figure 12. As would be expected from the predicted deflections, these analyses show much higher negative moments than the multi-stage analyses. These high negative moments are not supported by the measured steel stresses shown in figure 13. It should also be noted that a single stage analysis gives no indication of the moments in the structure when the fill is at the crown, which is invariably the critical load case for positive moment.

Figure 14 is a plot of crown deflection against maximum reinforcement tensile stress, for the standard multi-stage analysis (elastic concrete properties) and the values measured on site. It can be seen that the analysis has modelled the stress-strain history of the actual structure quite closely, with predicted reinforcement stresses being on the conservative side.

6.4 Soil Pressures

The soil pressures predicted by the multi-stage analysis are compared with the site measurements in Figures 15 – 17. The agreement between site measurements and analysis results is much less close than for the deflection and steel stress measurements, especially for the K values (horizontal pressure/vertical pressure). Possible reasons for the poorer fit include:

- Soil pressure is notoriously difficult to measure accurately, being very sensitive to the manner of installation of the pressure cells.

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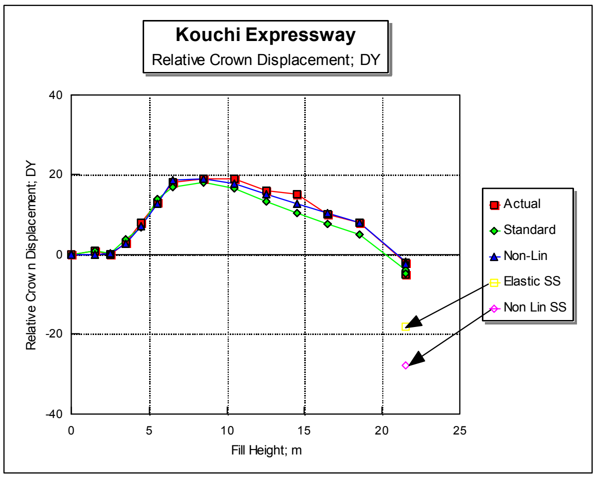

Figure 9; Vertical deflection at crown

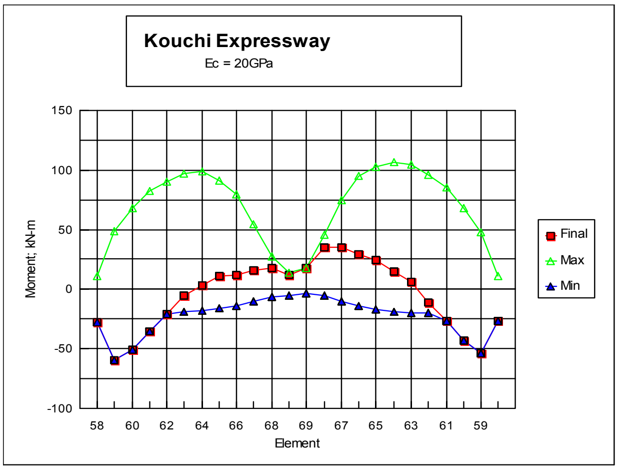

Figure 10; Bending Moment Envelope, Ec=20GPa

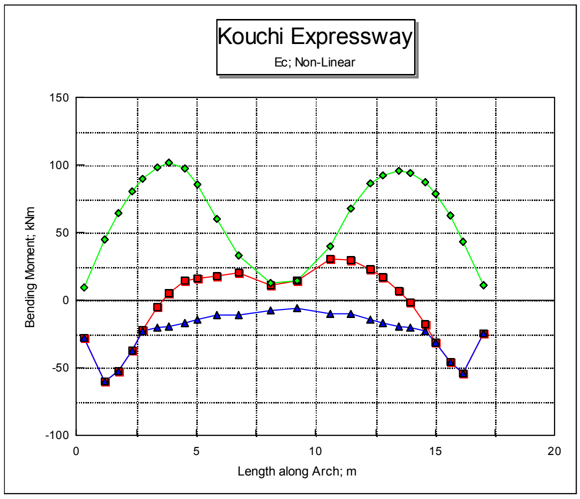

Figure 11; Bending Moment Envelope, Non-linear Ec

- The soil properties used in the analysis were chosen for a typical select backfill (as is normal in a practical design situation), rather than using measured properties of the actual material.

- The natural variability of soil makes its behaviour subject to random variation.

- The effect of compaction and other heavy plant can only be modelled in a simplistic way in the analysis.

In spite of the less precise agreement between actual and predicted soil pressures the important design values (forces and deflections in the concrete) were predicted with a good level of accuracy.

7 CONCLUSIONS

Multi-stage finite element analysis was found to give excellent agreement with site measurements of deflections and reinforcement stresses. In this case the analysis using linear elastic concrete properties (with a modified concrete modulus) gave results very close to the non-linear analysis. Although the closeness of the results may have been somewhat fortuitous in this case, it does indicate that the assumption of linear elastic concrete properties, with an appropriate modulus, is a practical design tool for normal buried arch structures.

Analysis assuming a single stage of loading was found to give poor correlation with site measurements, regardless of the behaviour assumed for the soil; indeed the use of a non-linear model gave worse results than the linear elastic analysis in this case.

8 ACKNOWLEDGEMENTS

The author wishes to thank the Sumitomo Corporation of Japan for their permission to publish the results of their site monitoring and measurements.

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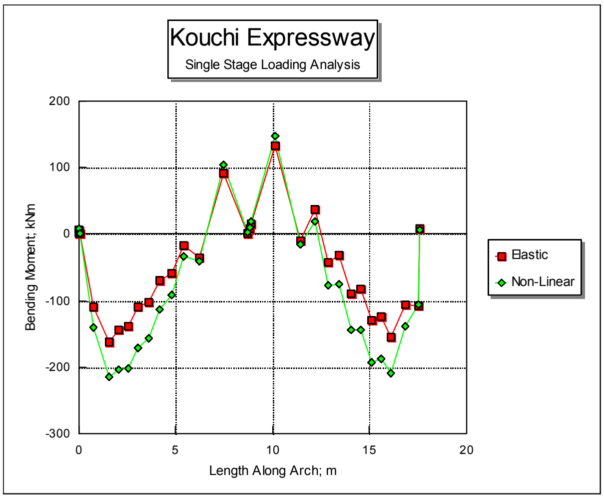

Figure 12; Bending Moment, single stage loading

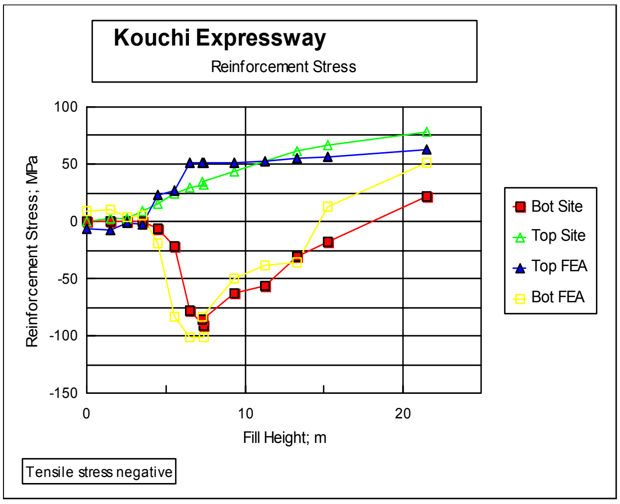

Figure 13; Reinforcement stress

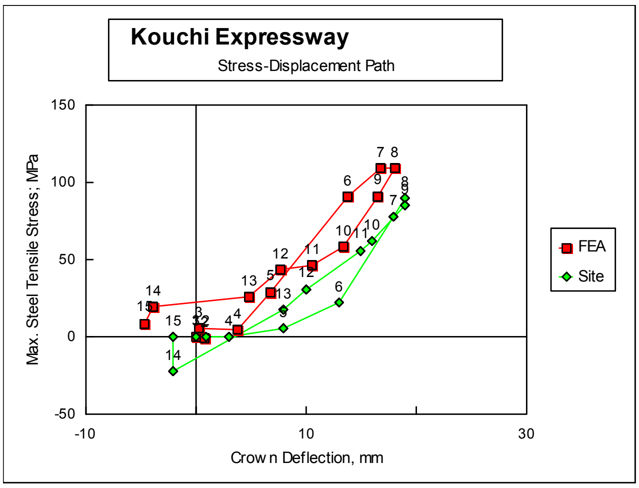

Figure 14; Stress-displacement path

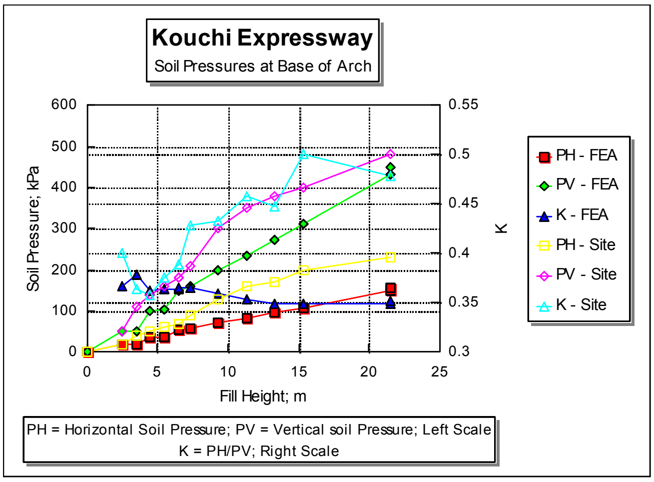

Figure 15; Soil pressure at base

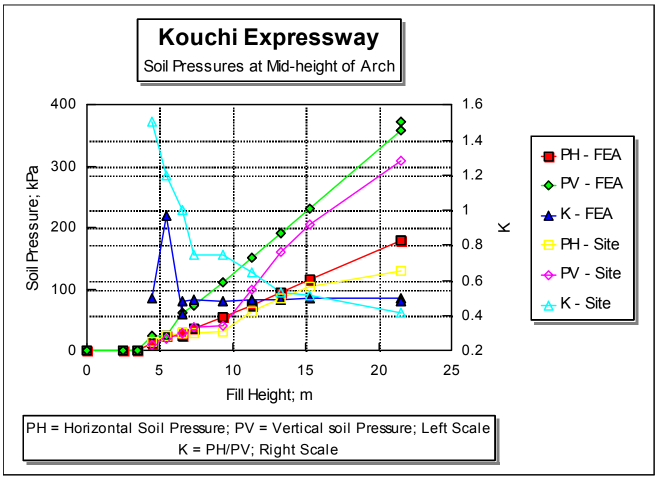

Figure 16; Soil Pressures at mid-height

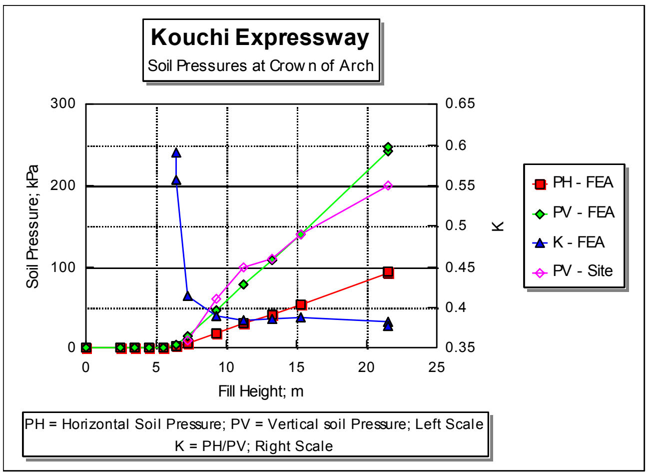

Figure 17; Soil pressures at crown