SEISMIC ANALYSIS OF BURIED ARCH STRUCTURES

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SUMMARY

This paper summarises results from the initial stage of a continuing study directed at developing an earthquake design procedure for buried concrete arch structures based on site specific finite element analyses. The present and earlier studies indicate that the complex dynamic nonlinear interaction of the soil and arch during earthquake loading can be satisfactorily simplified for design purposes by using static elastic analyses incorporating equivalent secant soil moduli. However, dynamic amplification effects need to be included in the static analysis to provide acceptable accuracy in the arch section force actions. Results show that the bending moments in the arch from horizontal earthquake loading can be significant in relation to the gravity load actions. These moments are also very sensitive to the backfill and surrounding soil stiffness properties and rather less sensitive to the foundation soils beneath the arch.

INTRODUCTION

The TechSpan® arch system is a two-piece, three-hinged buried precast reinforced concrete arch. The arch shape is designed to be a funicular curve under gravity loading. Since the introduction of the system by Groupe TAI in 1986 over 500 arches have been completed to site specific designs using a design method based on finite element analysis. Many have been used for highway and railway underpasses, and large hydraulic culverts. The arch may span from 4 to 20 m and typically is used to support earth fills from 1 to 30 m, and occasionally up to 60 m. Applications are likely to increase as the system has proven to be economical and quick to construct.

Buried arch structures are know to perform well under earthquake loading and in areas of low seismicity normal factors of safety used for gravity loading are likely to provide sufficient reserve strength in the arch to resist the design earthquake loads without the need for additional reinforcement. However, in areas of high seismicity such as North America, Japan and New Zealand, earthquake loading may become more critical and it is important to develop a satisfactory earthquake analysis and design procedure for application in these countries.

The design procedure for gravity loads uses an in-house nonlinear finite element package (Aztech) which applies the soil load in a series of layers to simulate the construction procedure. Results from this program have been verified against other finite element programs and site measurements. Although the gravity load design procedure is now well established there is uncertainty about the reliability of a number of options available for the design for earthquake loading. Most design specifications give no guidance and there is little published research available on the earthquake design of buried arch structures.:

[Byrne et al, 1994] carried out studies of the seismic response of TechSpan® arches and compared the results of static and dynamic analyses of two individual TechSpan® structures. Reinforced Earth Company of Australia (RECO) have analysed a number of recent designs and the same structures investigated by [Byrne et al, 1994] using the latest version of Aztech, which allows the application of vertical and horizontal accelerations. The results of these previous studies have been reviewed and extended with the following objectives

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- To validate the results of a static seismic analysis using Groupe TAI's in-house Aztech program.
- By carrying out simple dynamic analyses establish whether static methods satisfactorily account for dynamic effects and provide satisfactory results for design.
- To establish guidelines and limits for the application of seismic analysis methods in practical design.

This paper summarises the results of the first stage of the present investigation

2. GEOMETRY AND METHOD

Dimensions of the concrete arch structure investigated in the study are shown in Figure 1. The Arch has an inside span of 10.5 m, an internal rise above the base of 5.2 m, and a concrete section thickness of 300 mm. Analyses were carried out for both a 3 m and 15 m depth of soil cover above the top of the arch crown. The same arch dimensions were used for both depths of cover.

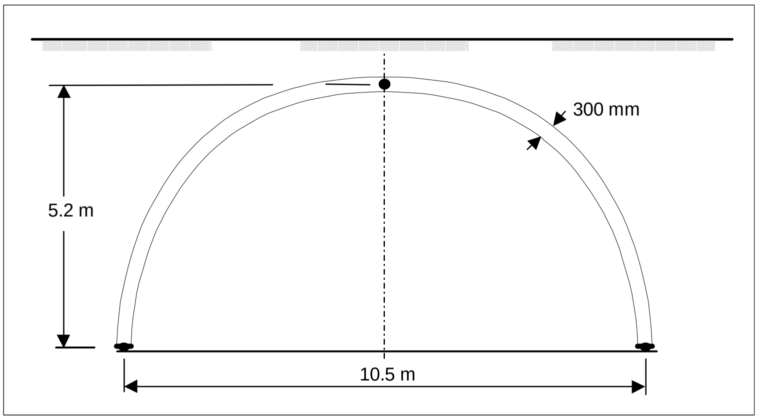


Figure 1. Arch shape.

Details of the finite element mesh are shown in Figure 2. The meshes for the two models were similar with the higher cover depth model having additional soil layers above the arch. Only one-half of the structure was modeled with the appropriate anti-symmetric or symmetric boundary conditions used on the arch centre-line and at the remote end of the soil layer to impose the correct deformations for either horizontal or vertical loading.

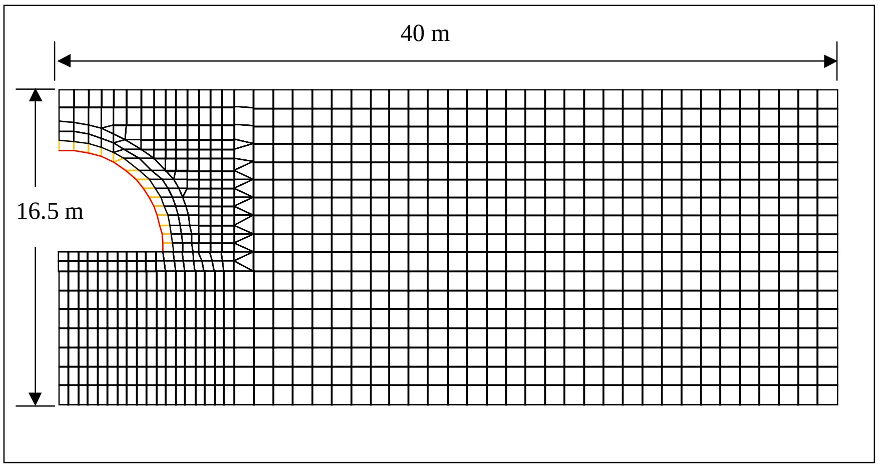


Figure 2. Finite element mesh – 3 m depth of cover.

The lateral extent of the mesh was taken as 40 m from the arch centre-line for the low cover model and 80 m for the high cover case. Preliminary static analyses indicated that the lateral extent should be at least three times the depth from the ground surface to the base of the arch. Smaller mesh lengths will result in significant errors in the computed arch actions under horizontal loading.

Three elements, each of radial width 500 mm, were constructed around the outer circumference of the arch to enable soil areas of light compaction to be included. For the gravity load case the horizontal layers above the base of the arch were added sequentially to simulate the construction process. Nine and 21 layers were used respectively for the 3 m and 15 m depth of cover models.

An 8 m deep soil layer with uniform soil properties was included beneath the arch base. Both cases of a rigid and flexible foundation were analysed by varying the properties of this soil layer. The appropriate depth of the layer to be included in the analysis is dependent on the variation of soil properties beneath the arch. Ideally the soil layers should be modelled down to rock but for deep soil sites this might not be practical. To check the sensitivity of the arch actions to the foundation layer depth the 8 m foundation layer was increased to 16 m. For the 15 m cover model this resulted in an increase of all the peak arch actions (bending moment, axial and shear force) of between 4% to 6%. The foundation soil in this analysis was assumed to be have a Young's modulus of 100 MPa and softer soils would result in larger differences. In most situations it is unlikely that the actions in the arch will be significantly in error if the foundation layer is taken to have at least the same depth as the depth from the ground surface to the base of the arch.

Elastic static and dynamic analyses were undertaken to determine the arch actions under horizontal and vertical earthquake loading using the MSC Nastran for Windows program. This software has the capability to carry out nonlinear static analysis but at the present time this refinement has not been used. The soil was modeled with 4-noded plane-strain quadrilateral elements and the half-arch section with 2-noded beam elements.

3. MATERIAL PROPERTIES

The soil was assumed to have an initial tangent shear modulus defined by the [Seed and Idriss, 1970] simplified equation:

$$G = 218.8\,(K_2)_{max}\,(\sigma'_m)^{1/2} \quad \text{in kPa units} \qquad (1)$$

Where,

σ'_m = mean principal stress: taken as 0.6 of σ_o, the overburden stress.

$(K_2)_{max}$ = soil modulus coefficient taken as 35 for compacted backfill and 20 for the light compaction layer.

Typically $(K_2)_{max}$ ranges from about 30 for loose sand to about 75 for dense sands, and is in the range of 80 to 180 for relatively dense gravels. Although the value of $(K_2)_{max}$ used was on the low side it gave initial tangent moduli values consistent with those used in a previous Techspan® arch investigation by [Byrne et al, 1994]. For design purposes it is also prudent to use soil stiffness values at the lower end of the likely range to ensure that the earthquake force actions computed in the arch section are not underestimated.

Equivalent secant moduli for the elastic finite element analyses were computed from the [Seed et al,1986] G/G_{max} versus cyclic shear strain (γ) curve for gravel (reproduced in Figure 3), using a one-dimensional stress-strain spreadsheet analysis of a shear layer with depth equal to the distance from the ground surface to the base of the arch. These equivalent nonlinear soil properties derived from cyclic shear strain results were considered

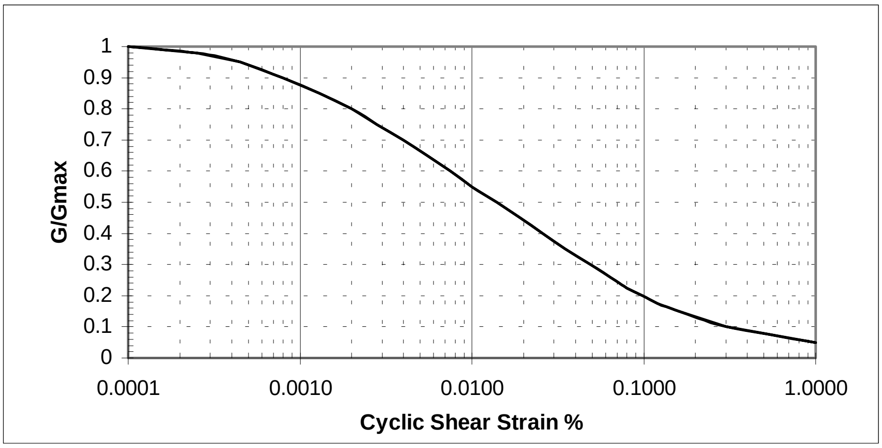


Figure 3. Shear modulus variation with shear strain. From [Seed et al, 1986].

appropriate because the earthquake response of the surrounding soil layers is not greatly modified by the presence of the arch leading to a predominantly shear layer response of the soil mass under vertically propagating shear waves. The earthquake loading was applied as a uniform horizontal body force in four equal increments to give a total inertia load corresponding to 0.2 g acceleration. This level of loading was used in previous nonlinear analyses and to simplify comparison of results was adopted for the present investigation. It is also an appropriate design level for areas of low to moderate seismicity.

The initial tangent and the derived secant moduli for application in the elastic analyses are shown in Figures 4 and 5 for the 3 m and 15 m depths of cover respectively. The lightly compacted layer with reduced stiffness properties (see Figures 4 and 5) was assumed to extend a distance of 1.0 m measured radially from the arch. In order to check the sensitivity of the arch actions to the soil stiffness properties the static analyses for both depths of cover were also carried out with the basic secant shear moduli values reduced by a factor of 2. To model rigid foundation conditions a Young's Modulus of 20 GPa was used for soil in the layer beneath the arch base. To investigate flexible foundation conditions this value was reduced to 100 MPa.

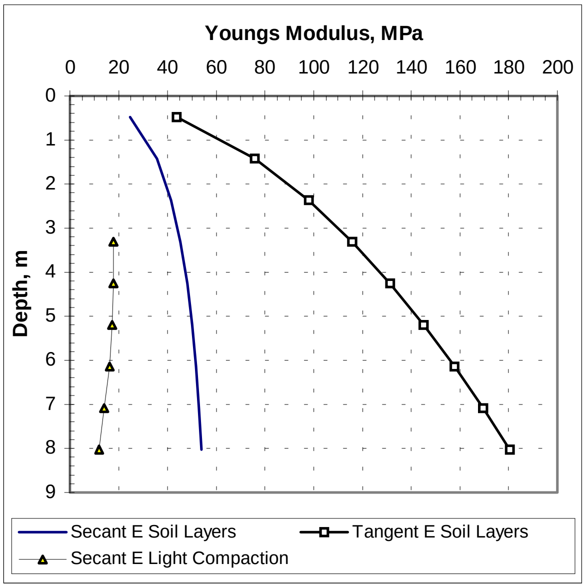


Figure 4. Variation of E with depth. 3m cover depth

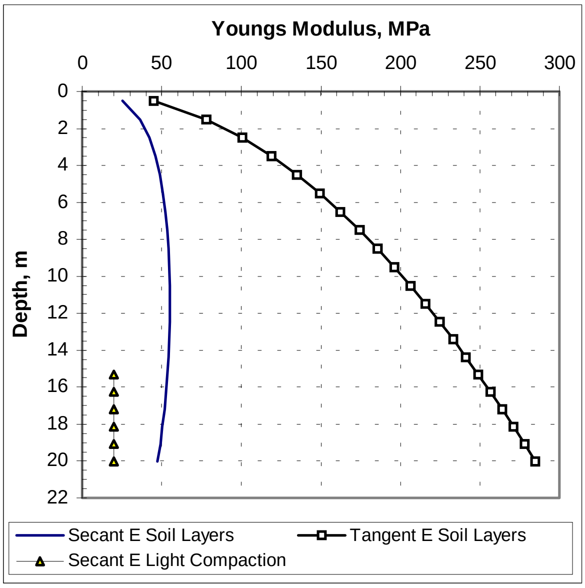


Figure 5. Variation of E with depth. 15m cover depth

Overall four sets of different soil material properties were used to investigate the sensitivity of the arch actions to soil stiffness, foundation flexibility and light compaction layer properties. These sets were referred to as Model A, B ,C and D and their soil equivalent secant Young's Moduli are summarised in Tables 1.

Table 1. Secant Young's Moduli for Soil Layers

Cover Depth metres	**Soil Layer Location**	**Model A Basic** E, MPa	**Model B Red. Soil E** E, MPa	**Model C Flex. Found** E, MPa	**Model D No Light Comp. Zone** E, MPa
3	Top Soil Layer	24.7	12.4	24.7	24.7
3	Bottom Soil Layer	53.8	26.9	53.8	53.8
3	Top Light Compaction	17.9	9.0	17.9	48.0
3	Bottom Light Comp.	12.0	6.0	12.0	53.8
3 & 15	Foundation Layer	20000	20000	100	20000
15	Top Soil Layer	25.2	12.6	25.2	25.2
15	Bottom Soil Layer	47.2	23.6	47.2	47.2
15	Top Light Compaction	20.0	10.0	20.0	53.5
15	Bottom Light Comp.	20.0	10.0	20.0	47.2

A Poisson's ratio of 0.3 was assumed for all soils. The mass densities of the lightly and fully compacted fill were taken as 2.0 and 2.1 t/m^2 respectively. The concrete in the arch was assumed to have a Young's modulus of 20 GPa, Poisson's ratio of 0.2, and a mass density of 2.4 t/m^2.

4. ANALYSES AND LOADS

A static elastic analysis and two separate response-spectrum normal-mode dynamic analyses were undertaken for each depth of cover. For the static load case the two depths of cover and the four models with different material properties were considered. Only Model A properties were used in the dynamic analyses but both depths of cover were investigated. Earthquake loading in the static analysis was represented by an 0.2 g acceleration applied as an uniform horizontal body force to all elements in the model.

In the response-spectrum normal-mode analyses the following two horizontal earthquake acceleration spectra were used for input loading:

- A spectrum with constant 0.2 g spectral ordinates for all periods of vibration. This spectrum approximates the short period response of a system with very high damping and was used to identify dynamic effects that were not associated with amplification by the input response spectrum function.
- The Standards New Zealand Loading Code (NZS 4203: 1992) elastic spectrum scaled for 20% damping and to 0.2 g zero period ordinate on a deep soil site. The 20% damping spectrum shown in Figure 6 was computed from the 0.2 g, 5% damping spectrum, by applying a reduction factor of 0.67. Damping of 20% was estimated from the [Seed et al, 1986] damping versus strain curves to be an appropriate average value for the range of shear strains expected under the 0.2 g zero period ordinate earthquake.

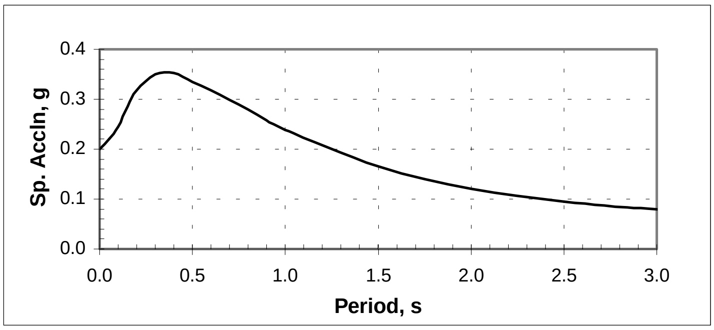


Figure 6. Scaled NZS 4203 Spectrum. 20% damping.

5. RESULTS

Static Analyses

Preliminary static analyses carried out to verify the Aztech nonlinear program for horizontal loading showed good agreement between both the Aztech and [Bryne et al, 1994] model results with the arch actions from the present 3 m and 15 m depth of cover models analysed with equivalent soil properties.

Model A, B, C and D arch section bending moments, axial and shear forces for the 3 m depth of cover are compared in Figures 7 to 9. Similar comparisons for the 15 m cover depth are shown in Figures 10 to 12.

The Model A and B results for both the 3 m and 15 m cover depths showed that the arch bending moments were very sensitive to the range of soil properties considered, with the peak values increasing between 84% to 90% when the soil elastic moduli were reduced by a factor of 2. A similar increase was observed in the peak shear forces. In contrast, the axial forces are less sensitive showing a 10% to 17% decrease in peak values.

The effects of increasing the foundation flexibility and removing the light compaction layer are illustrated by the Models C and D results. For both depths of cover, the flexible foundation produces an increase of between 13% to 27% in peak bending moments and axial force, and a 50% to 60% increase in peak shear forces. In contrast, the light compaction layer has little effect on the bending moments and shear forces but its removal produces a 30% to 60% increase in the peak axial forces.

Dynamic Analyses

The Model A arch actions from the static and two dynamic analyses are compared in Figures 13 to 15 for the 3 m depth of cover and in Figures 16 to 18 for the 15 m depth of cover. For the 3 m cover depth all three peak dynamic arch actions from the 0.2 g constant spectrum are significantly greater than the corresponding peak

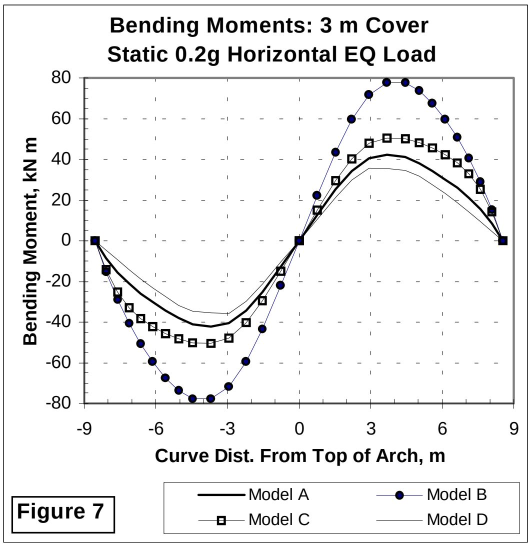
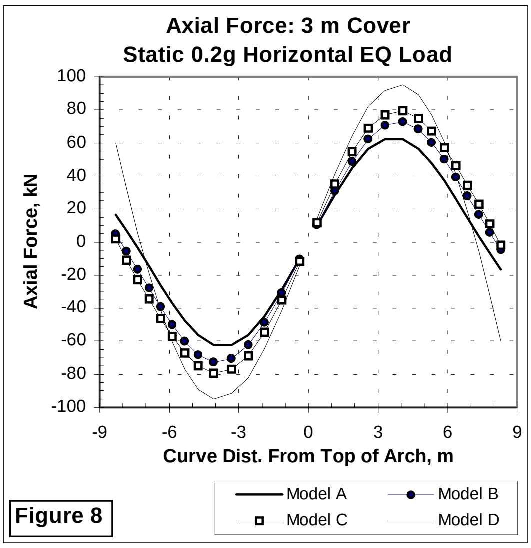


Figure 7



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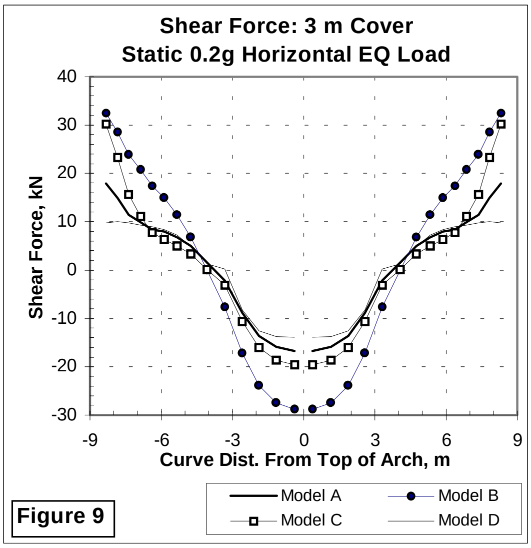

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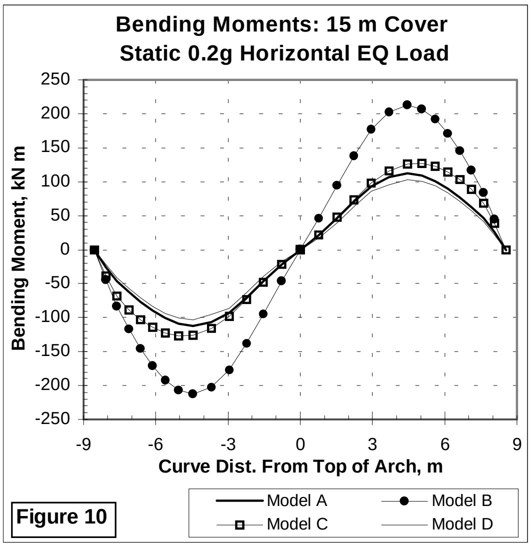
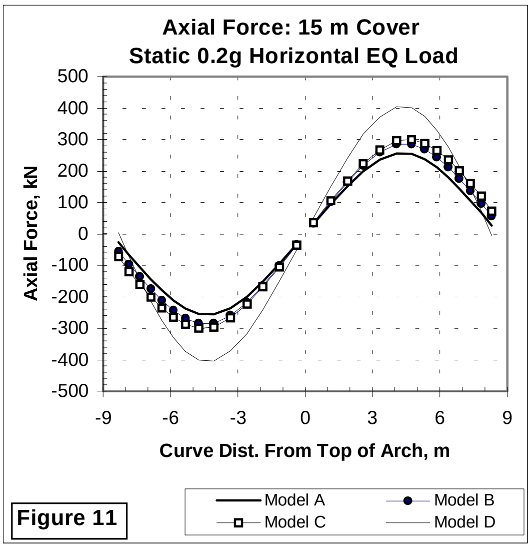


Figure 10



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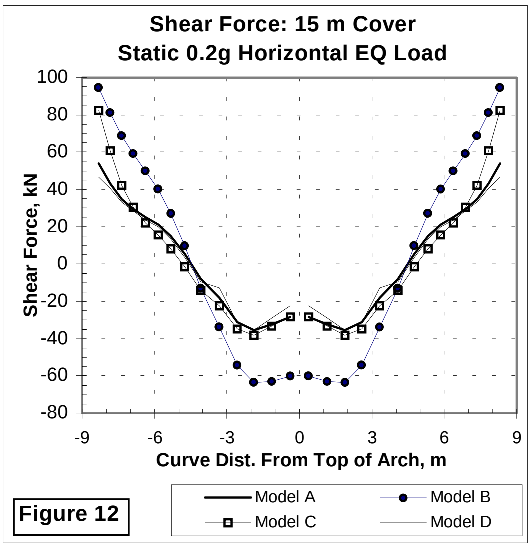
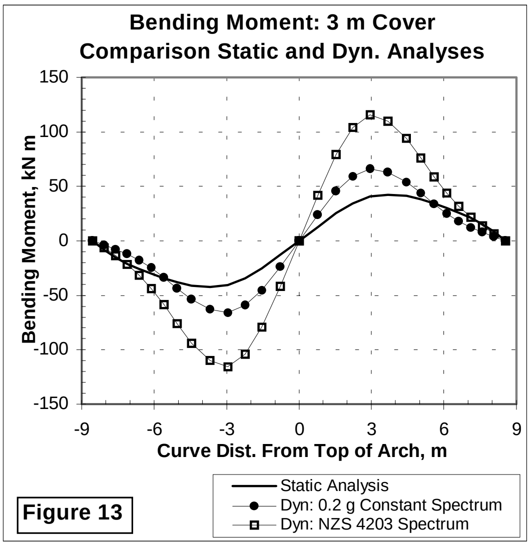


Figure 12



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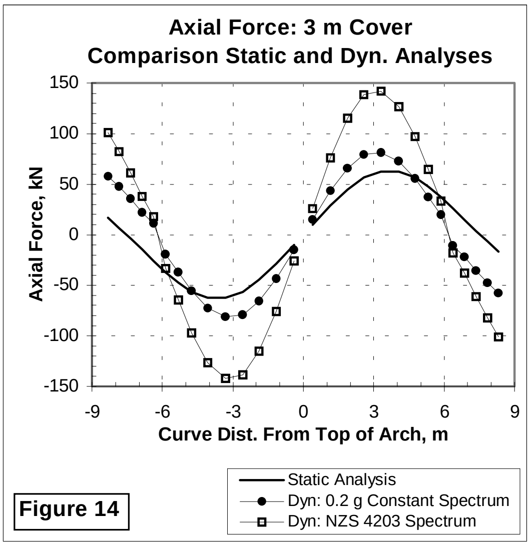

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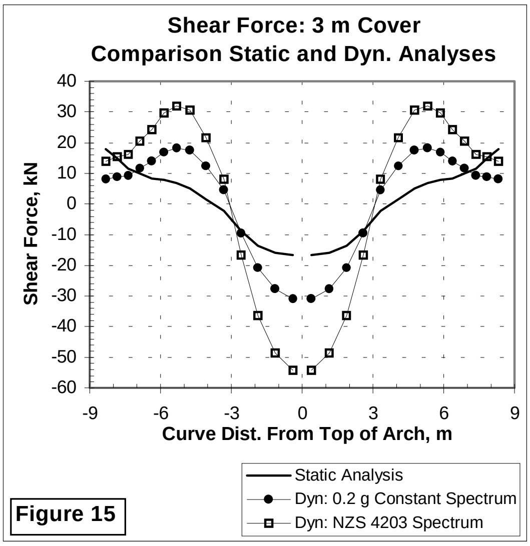

Figure 15

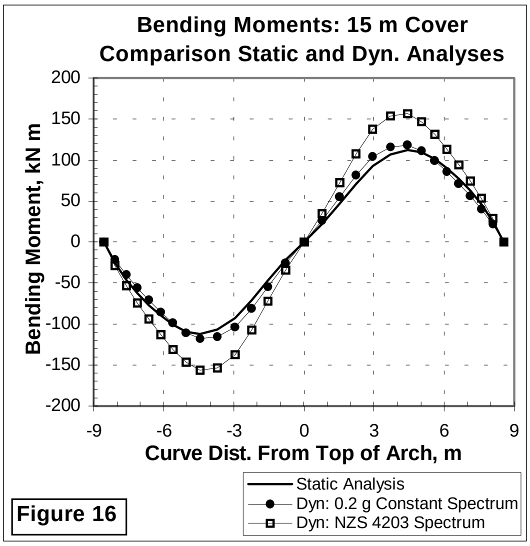

Figure 16

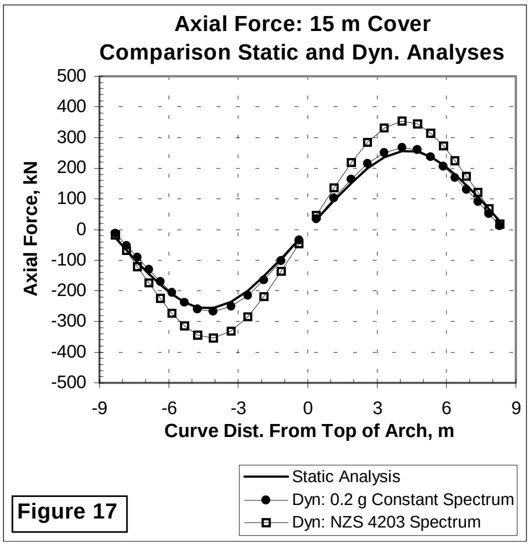

Figure 17

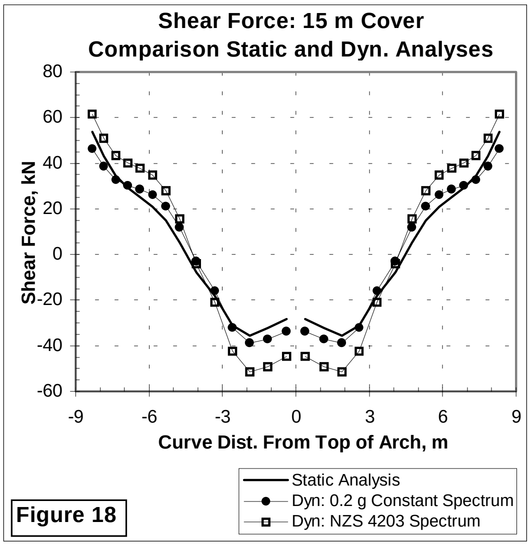

Figure 18

static values with the peak bending moments about 55% greater and the peak axial forces about 30% greater. For the 15 m cover depth all three peak dynamic arch actions were greater than the corresponding peak static values but at this depth the increases were less than 10%. The peak accelerations computed in the soil mass by the dynamic analyses increased near the cavity created by the arch. This disturbance of the shear layer response is much more pronounced for the shallow depth where the cavity is large in relation to the layer depth leading to a larger increase in the arch actions between the static and dynamic loading cases.

For the 3 m cover depth all three peak dynamic arch actions from the NZS 4203 spectrum loading are significantly greater than the corresponding peak static values with the peak bending moments about 170% greater and the peak axial forces about 130% greater. For the 15 m cover depth all three peak dynamic arch actions were greater than the corresponding peak static values but for this greater depth the differences were not as large being about 40% for both peak bending moment and axial force, and about 15% for peak shear force.

Inspection of the modal response components showed that for the 3 m depth of cover about 95% of the dynamic actions in the arch were generated by response in the lowest vibration mode. The soil layer deformations in this mode closely resemble the shearing type of deformations that occur in the lowest horizontal mode of a soil layer of large lateral extent. For the 15 m depth of cover the contribution of the first mode to the total dynamic arch actions was about 98% indicating a very small contribution from higher mode response. The lowest mode periods of vibration were 0.41 and 0.86 s respectively for the 3 m and 15 m depths of cover. Inspection of the scaled NZS 4203 spectrum (Figure 6) shows that the corresponding amplification factors for the first mode response would be about 1.9 and 1.3 respectively. This amplification leads to most of the increase between the static and dynamic arch actions with a smaller contribution coming from the cavity effect.

Because of the adoption of a simple elastic analysis method the soil properties were not adjusted for the larger soil strains that would result from the amplification and other dynamic effects. The influence of these larger strains on the arch actions can be estimated by using the results from both Models A and B which show the effects of softening soil properties. Alternatively more sophisticated nonlinear analyses can be used.

6. CONCLUSION

The bending moments in the arch from horizontal earthquake loading are very sensitive to the soil stiffness properties with the moments increasing as the soil stiffness reduces. The shear forces are also sensitive to the soil stiffness but the axial forces are much less sensitive. All three actions in the arch are moderately sensitive to the stiffness properties of the foundation soil with all three increasing with decreasing foundation soil stiffness. Soil areas of light compaction close to the arch affect the axial forces but only have a minor affect on the other actions.

The dynamic analyses showed that the cavity created in the soil layers by the arch resulted in significant increases in all three actions in the arch for the 3 m depth of cover. This increase was attributed to an increase in the soil mass accelerations near the cavity. For deeper cover depths where the cavity dimensions are quite small in relation to the overall soil layer depth this dynamic effect was less pronounced.

Under dynamic horizontal earthquake loads the response of the arch is dominated by the shear layer first horizontal mode response of the surrounding soil. Providing allowance is made for any amplification of the input motions by the shear layer, simple static analyses using uniform body forces will give a satisfactory estimation of the arch actions for moderate to deep cover depths. The static uniform body force magnitude should be estimated by computing the first horizontal mode period of the soil layer and using the spectral acceleration at this period.

7. REFERENCES

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