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FINITE ELEMENT ANALYSIS AND FIELD INSTRUMENTATION OF A SOIL/CEMENT ARCH

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ABSTRACT: A two dimensional plane strain finite element analysis is used to predict the increase in stress on an existing tunnel caused by the addition of twelve feet of fill. The fill, soil/cement, was placed in the shape of an arch over the existing tunnel. An instrumentation monitoring program was initiated to evaluate the potential stress increase on the tunnel roof and side walls to confirm the analysis.

INTRODUCTION

The fill over an existing concrete box tunnel was to be increased by twelve feet in two phases, each phase consisting of the placement of six feet of fill. The factor of safety of the existing tunnel was such that it could not safely support the increased loads from the fill. In order to minimize the stress increase on the tunnel, the fill was designed as a soil/cement arch, reinforced with geogrid, which would span the tunnel transferring loads away from it.

The soil/cement arch which was designed based on structural mechanics consists of an expanded polystyrene base, soil/cement and geosynthetic reinforcement. Figure 1 shows the arch and its components in further detail. The haunches of the arch were angled away from the tunnel such that the change in stress from the weight of the fill would be minimal at the tunnel side walls, and effectively zero on the tunnel roof, thus assuming the arching effect transfers all of the load to the haunches. Boussinesq stress distribution was initially utilized to evaluate the appropriate haunch angle. The arch was constructed by mixing cement with the site soils and placing and compacting it as conventional fill. The cement provides a substantial increase in the shear strength of the sand fill (on the order of 500 psi unconfined strength) such that the stresses from the weight of the fill can be redistributed and carried by the outside haunches of the arch. Two layers of geogrid (Tensar SR-2) were placed at the invert of the arch to provide lateral restraint during

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construction and to increase the factor of safety against tensile failure in the bottom of the arch during curing of the soil/cement. The grid was selected based on the tensile resistance required to support the full weight of the arch and strain compatibility with the soil/cement material. To allow the arching action to take place, the material directly below the center of the arch must deform vertically more than the total settlement of the haunches of the arch during and after construction. To allow for this deformation, compressible porous expanded polystyrene (EPS) panels were placed beneath the arch. The EPS panels were specially manufactured for this project based on the deformations required to achieve the arching action.

In order to check the design and evaluate the stresses on the tunnel caused by the twelve foot increase in soil embankment height, a finite element method (FEM) analysis was performed. The FEM solution was obtained using an incremental finite element computer program for two-dimensional plane strain analysis, FEADAM 84 (J.M. Duncan, et al, 1984). Although limited information was available for conducting a FEM analysis, conservative assumptions allowed for its utilization in confirming the validity of the design approach.

The results of the numerical analysis showed that the soil/cement acts effectively as an arch to substantially reduce the stresses that would be transferred to the tunnel crest and sidewalls due to the embankment construction. An instrumentation monitoring program was initiated prior to construction of the first phase (six foot fill height) of the soil/cement arch to evaluate the potential stress increase on the tunnel roof and sidewalls.

This paper provides a review of the numerical analysis along with field instrumentation data which corroborates the design approach.

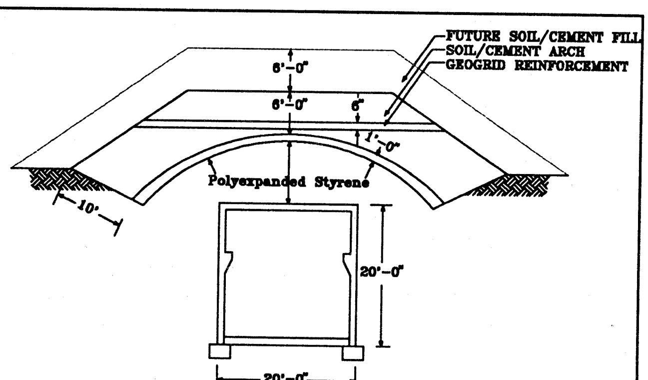


Figure 1. SOIL/CEMENT ARCH

EXISTING CONDITIONS

The tunnel was approximately eighteen feet square, inner dimensions with the walls and roof 12 to 15 inches thick. Structural analysis of the stresses on the tunnel from the existing loads, assuming a uniform load on the tunnel roof corresponding to the weight of the soil acting on the structure, and an at-rest lateral earth pressure for the tunnel side walls, indicated that the design of the tunnel was adequate to just meet standard design criteria. The tunnel was unable to carry a substantial increase in load from the proposed fill.

There was little, if any, data available on the performance of the existing structure under the existing loads. Some information was, however, available on the original soil conditions. Based on subsurface exploration information, including Standard Penetration data, the soils consisted of dense sand below the structure with backfill of undetermined quality surrounding the structure. The relative lack of information available on the existing soil conditions was a concern for the designers. However, because of the severe time restraints, three weeks to design the soil/cement arch and produce plans and specifications, additional borings and laboratory testing could not be conducted. Conservative soil properties were, therefore, used that would produce larger deformations and stresses than actually anticipated. Additional subsurface information was obtained during the analysis which generally confirmed the soil parameter assumptions.

FEM ANALYSIS

In order to evaluate the stresses on the existing tunnel caused by the 12 foot increase in soil embankment height, a finite element method analysis was performed using FEADAM 84. FEADAM 84 is an incremental finite element program for two-dimensional plane strain analysis of earth and rockfill dams and slopes. It calculates the stresses, strains, and displacements due to incremental embankment construction. The program calculates the stresses, strains, and displacements in embankments and slopes, simulating the actual sequence of construction operations. The non-linear and stress dependent stress-strain properties of the soils are approximated by performing the analysis in increments. The design engineers considered using other FEM programs (e.g. SSTIPN) that allow for more direct soil-structure interaction modelling, by the use of structural elements and interface elements. However, because of time constraints, FEADAM 84, which was readily available to the design engineers was selected for the analysis.

The finite element mesh used for the analysis was developed after several smaller meshes were analyzed. Figure 2 shows the final finite element mesh idealized for the model, with the nodes, elements and soil materials. The model consisted of 1145 nodes, 1145 elements and 5 material types. A full scale model was constructed in lieu of a symmetrical half model based on non-symmetrical behavior observed in the preliminary analysis. Several factors appear to have contributed to the non-symmetrical behavior including large deformations on the order of 30% strain, in the EPS panels. In a symmetrical half model these deformations would occur in elements at the boundary. It has been found that such large deformations in boundary elements can present difficulties in FEM analysis. Further, because of the complex geometry of the soil/cement arch many triangular shaped elements were used in the model. The use of these elements may also contribute to small differences in stress associated with some similar elements on either side of the center line of the model.

A very dense stratum was assumed to be present at a depth of 20 feet below the tunnel. Therefore, the model was fixed in the vertical and horizontal direction by using hinges at that elevation. The model was extended 20 feet beyond the edges of the arch and roller joints allowing for vertical movement but restraining horizontal deformation were used at that boundary.

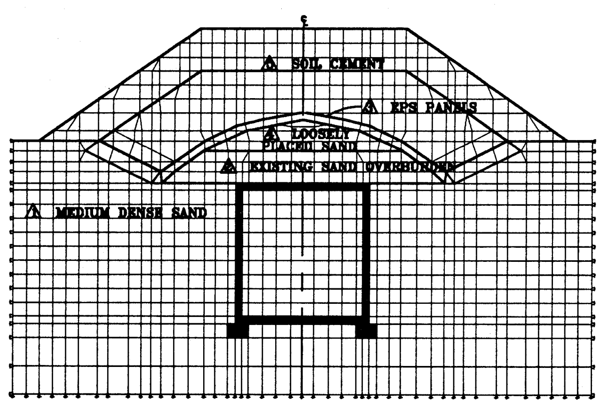


Figure 2. FINITE ELEMENT MESH

Soil Properties. A hyperbolic model was used to describe the non-linear, elastic behavior of the various soil stratum and EPS panel strata. Table 1 lists the value of the parameters. These values were estimated based on limited soil information which was compared with average values for similar soils reported by Duncan et al., 1980. The soil/cement which was reinforced with geogrid was characterized as a homogeneous material with a friction angle of 35° and a cohesion of 7.2 tons per square foot. The properties used for the soil/cement were derived from in-house unconfined compression test data in conjunction with information provided by the Portland Cement Association on soil/cement properties. Due to the inability of FEADAM 84 to effectively model the soil reinforcement interaction, the effect of the reinforcement was conservatively ignored in the analysis.

The compressive EPS panel characteristics were modeled by actually constructing a simple finite element model of a compression test and matching the values to those obtained in a laboratory compression test.

The analysis was conducted in three stages. First, the model was constructed for the existing soil conditions at the base of the arch, at a height of 9 feet above the tunnel. This represented the existing conditions prior to arch construction. The placement of the soil/cement arch to a height of 16 feet above the tunnel crest was evaluated next. The final analysis included placement of the fill to a height of 22 feet above the tunnel crest.

Table 1. Summary of Hyperbolic Parameters Used in Program FEADAM84

Property	Soil Type* 1	2	3	4	5
(1) Unit Wt., tcf	0.065	0.055	0.01	0.05	0.065
(2) Modulus No. K	700.	300.	0.2	250.	5000.
(3) Unload Mod. No. K_{ur}	800.	900.	0	900.	6000.
(4) Modulus exponent, N	0.3	0.3	0	0.3	0.4
(5) Failure Ratio R_f	0.7	0.7	0	0.7	0.8
(6) Bulk Mod. No. K_b	300.	150.	0.6	100.	2000.
(7) Bulk Mod. Exponent, m	0.1	0.1	0	0.1	0.1
(8) Cohesion, C, tsf	0	0	0.05	0	7.2
(9) Friction Angle, ϕ_o at p=1 atm, degrees	35.	32.	5.	30.	35.
(10) ϕ per log cycle change in $sigma_3$, degrees	4.	2.	1.	2.	6.
(11) K_o approximates 1-Sin ϕ_o	0.25	0.3	0.2	0.33	0.2

*Soil Type	Location
1	Existing soil
2	Existing overburden over tunnel
3	EPS panels
4	Backfill soil beneath arch
5	Soil/cement

For soil locations see Figure 2.

Each stage was constructed incrementally to simulate actual construction of the embankment. A total of 9 construction layers was used in the final analysis. Due to time restrictions, the tunnel was not modeled as a separate stiff unit. However, by simply modeling the tunnel as soil elements, the stress levels at the tunnel can be approximated.

The FEM analysis was used not only to predict the relative increase in stress on the tunnel caused by the increased height of fill over the tunnel, but also to determine the most economical haunch elevation for the arch. The minimum haunch elevation was selected by performing a parametric study of the tunnel varying the location of the bottom of the arch. By doing this we were able to minimize the excavation necessary for the arch supports.

PREDICTED STRESSES

The results of the analysis showed that the soil/cement acts effectively as an arch to substantially reduce the stress that would have been transferred to the tunnel crest and sidewalls due to the embankment construction. A vertical stress increase on the order of 10% to 20% above the existing stress was predicted for construction of the first phase of the embankment. Essentially, this increase simulates a height of fill of only 1.5 feet versus the actual 6 feet that will be placed. The second phase of arch construction will result in an even more substantial reduction in stress. The second phase increase in stress simulates a height of fill of only one foot versus the actual 6 feet that will be placed. In the first phase a majority of the stress occurred during construction of the arch prior to the arching action. Phase 2 construction will be supported by the load carrying action of the Phase I arch.

The sidewall evaluation is more difficult to compare with existing conditions as the actual stress transferred to the tunnel wall, existing and future, would depend on the stiffness of the tunnel and a good estimate of the initial conditions. If the tunnel walls move freely, an active stress condition would exist such that the existing stress conditions would be similar to that obtained after the first phase of the analysis with the existing soil extending 9 feet over the top of the tunnel. In this case, a 10% to 20% stress increase would be anticipated on the tunnel sidewalls. However, if the tunnel walls are relatively unyielding, an at-rest condition would exist such that the actual increase in stresses on the tunnel walls could be substantially different. In fact, the analysis indicates that the stress levels due to the arch would not cause any increase in stress on the tunnel side walls if the at-rest condition exists prior to arch construction. As there is an increase in outward thrust away from the tunnel wall, due to construction of the arch, the stress on the tunnel wall could theoretically decrease for the at-rest condition.

Field Instrumentation Program. An instrumentation monitoring program was initiated prior to the initial phase of construction. The primary purpose of the instrumentation program was to evaluate the potential stress increase on the tunnel roof and side walls at several locations within the construction area to confirm the analysis. Four stations along the length of the tunnel were instrumented. At each location inside the tunnel three bonded resistant strain gages were installed on the tunnel roof and three on the side walls of the tunnel. 100 millimeter long Micro-Measurement EP series strain gages, with an accuracy of less than 1% deviation with a 10 degree temperature change, were used to monitor changes in strain. The gages were installed directly on the concrete tunnel after first preparing the surface by degreasing and applying several coats of resin adhesive to the concrete. The gages were then directly applied to the adhesive. The gages on the tunnel roof were oriented in the transverse direction, perpendicular to the tunnel axis. The strain gages located on the tunnel wall were oriented vertically. At the same locations, tape extensometer bolts were installed on the walls and roof to monitor tunnel deflections (Figure 3).

Two inclinometers were installed to provide additional information on the change in stress on the tunnel due to the construction of the soil/cement arch. One inclinometer was installed approximately four feet from the tunnel to evaluate soil deformation towards or away from the tunnel during construction. The second inclinometer was installed 20 feet from the tunnel, outside the haunch of the soil/cement arch to evaluate the magnitude of deformation away from the tunnel at that location. Both inclinometers were installed at station No. 2.

Finally, three pressure cells were installed to directly monitor the change in stress in the soil caused by the addition of the six feet of fill. Two earth pressure cells (Pc_2 and Pc_3) were installed at the haunch of the arch, in an attempt to monitor the increase in stress at the base of the arch (Figure 3). The location of the gage at the soil and relatively stiffer soil/cement interface provided the best location to obtain accurate stress measurements without performing extensive in soil calibration. The third cell was located in the soil beneath the arch (below the EPS panels) to monitor the change in stress in the soil below the arch. This pressure cell was not located at the center line of the arch because the length of tubing required between the cell and the readout device would have been excessive. The results from this gage were considered qualitative due to complications in measuring stress transfer from the very low stiffness of the EPS panels compared to the soil and the pressure cell.

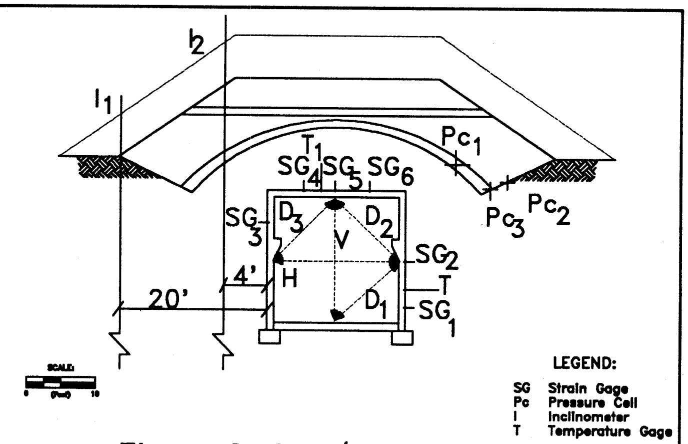


Figure 3. SOIL/CEMENT ARCH INSTRUMENTATION PLAN

Construction Procedures. The construction of the soil/cement arch involved excavation of 3 feet of the existing soils from elevation 98 to 95 over the top of the tunnel. Soil was then loosely backfilled over the tunnel in the configuration of the arch (soil type 2 shown on Figure 2). The haunches for the support of the arch were excavated above the sides of the tunnel.

The soil directly above the tunnel was excavated and then loosely backfilled for two reasons. First, in order for the arch to act as an arch, it must deform, thereby transferring load to the haunches. By loosening the soil below the center of the arch, larger arch deformations are permitted without substantially increasing the stresses on the tunnel roof. Secondly, by monitoring the strains within the tunnel walls and roof before and after this excavation, the strain gages could be field calibrated. Since the amount of soil removed is known, the changes in strain, on the order of 50 microstrain, associated with this excavation will allow for calibration of the magnitude of stress change during construction. After the existing ground had been reshaped to the desired arch configuration, EPS panels were installed. The panels were designed to allow arch deformation without substantially increasing tunnel stresses. Soil/cement was then installed in 8 inch lifts to construct the arch. The construction sequence was staged such that for any section of arch along the length of the tunnel, that section was completed each day (i.e., the backfilling of the soil/cement was continuous). Only construction joints parallel to the length of the tunnel were allowed.

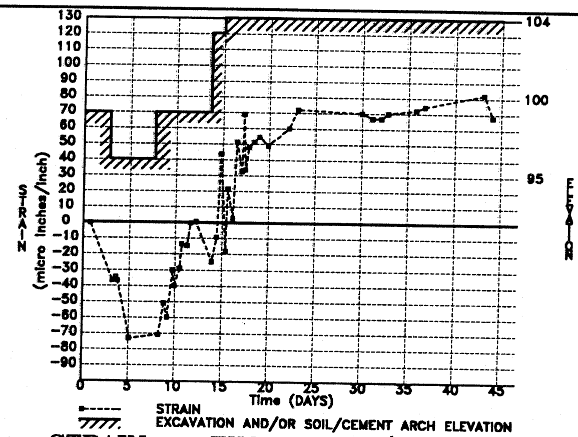
INSTRUMENTATION RESULTS

During the excavation (unloading) phase of the construction from approximately elevation 98.0 to elevation 95.0, the stain gages located on the roof of the tunnel reflected a negative strain ranging from -40 to -80 microstrain for an average strain of -60 microstrain for the three feet of soil. Therefore, an average change in strain of 1 microstrain corresponds to a change in vertical stress on the tunnel roof of approximately 6 pounds per square foot.

The final change in strain along the tunnel roof after completion of the soil/cement arch ranged from +15 to +90 microstrain with an average increase in strain across the tunnel roof of +50 microstrain. The range in strain across the tunnel roof was anticipated. Hard points created at the intersection of the tunnel walls with the roof allow for less deflection at the ends of the roof than at the center line. A non-uniform stress distribution is, therefore, created across the tunnel roof with higher vertical stresses at the corners than at the center line of the roof. To minimize the edge effects on the instrumentation data, the strain gages on the roof were located at the center line of the roof and halfway between the center line and the edge of the tunnel. The average increase in stress on the tunnel roof at these monitoring points was 0.138 tons per square foot. The FEM analysis predicted 0.087 tons. The measured strains correspond to a fill height of 2.5 feet. For actual fill height applied of 6 feet, the difference in actual verses predicted was attributed to the above mentioned edge effects and to construction stresses transferred to the tunnel roof prior to development of the arching action. Figure 4 shows the correlation between excavation/fill height versus strain for a typical roof strain gage.

Previously indicated sidewall analysis is analytically more complex than the roof analysis because the actual stress transferred to the tunnel walls is dependent on the stiffness of the tunnel. As previously indicated, if the tunnel side walls move freely, an active earth pressure stress condition exists. If the tunnel walls are relatively unyielding, an at-rest pressure condition exists, which could result in no increase in stress due to the arch.

Figure 3 shows the location of the strain gages along the tunnel side walls. Gage No. 1 was located 4 feet off the tunnel floor. The average measured strain at the four monitoring stations was 41 microstrain. The correlating field calibrated change in stress was .115 tons per square foot. This represents an increase in lateral stress of approximately 20%. Strain gage No. 2 experienced a change of stress of 0.026 tons per square foot or a 6% increase in stress. The average change in stress for gage No. 3 was 0.038 tons per square foot which is a 14% increase in stress.



STRAIN vs EXCAVATION/FILL HEIGHT
STATION #2 GAGE #6
Figure 4.

The change in strain and correlated change in stress based on the relationship established during the removal of the overburden soil, appears to indicate that the tunnel sidewalls are relatively flexible and that an active earth pressure condition exists. For this case, the finite element analysis predicted an increase in stress of 10% to 20%. The measured change was 6% to 20%.

Convergence tape bolts were installed in the tunnel floor, roof and sidewalls at the same monitoring stations as the strain gages. Deflections of the tunnel structure were monitored over the course of the construction of the soil/cement arch. The average change in deflections for all monitoring points, except the horizontal deflection at station No. 2 was less than 1 millimeter. The horizontal deflection at station No. 2 was 11 millimeters. The relatively large deflection at station No. 2 occurred overnight and is believed to be a readout error as no other changes at station No.2 were observed at that time. The primary purpose of the convergence tape monitoring system was to provide a back up monitoring system for the strain gages.

Two inclinometers were installed at station No. 2 to provide an additional indication of stress increase or decrease on the tunnel due to the construction of the soil/cement arch. The inclinometers were read on a daily basis during construction of the soil/cement arch at station No. 2 and once to twice a week for a period of approximately one month after construction of this segment of the arch was complete. The inclinometer data indicated no change in lateral displacement of the soil below the arch caused by the arch construction.

A very clear indication of the arching action was obtained with three Glotzl pressure cells, cell No.1 located below the polyexpanded styrene and pressure cells No. 2 and No. 3 located at the interface between the soil/cement arch and the existing soil at the haunch of the arch. The average pressure as measured by pressure cell Nos. 2 and 3 at the haunch of the arch was 1.34 tons per square foot representing an equivalent increase equal to over 20 feet of soil for the 6 feet actually applied. The FEM analysis predicted an average increase in stress below the haunch of 1.6 tons per square foot. The actual increase in stress was within 20% of the predicted value. Although the accuracy of cell No. 1 is suspect, the pressure as measured by cell No. 1 under the arch itself was 0.3 tons per square foot which is within 10% of the predicted stress from the FEM analysis.

CONCLUSIONS

A plane strain, two dimensional finite element method of analysis was successfully used to evaluate the design of a soil/cement arch structure, constructed to transfer stress away from a tunnel due to an increase in the fill height above the tunnel. Although numerous assumptions were required to expedite the analysis, the results provided qualitative confidence that the design was feasible and allowed construction to proceed within the severe time restraints required for completion of the project. Even with the required assumptions for material properties (not unusual in geotechnical practice), the results of the FEM analysis compare very well to the instrumentation results. The FEM analysis of the soil/cement arch predicted an increase in vertical stress on the tunnel roof of approximately 0.09 tons per square foot. The instrumentation and monitoring program measured the changes in stress and strain and were in general agreement with the FEM analysis, measuring a change in stress of 0.14 tons per square foot. The measured increase in stress on the tunnel roof corresponds to a fill height of 2.5 feet, the actual fill height was six feet. The final phase of construction (adding another 6 feet of fill) has not been started as of August 1990. As the first phase of arch construction will support the second phase, the additional increase in stress is anticipated to be proportionally lower than estimated by the FEM model.

This project demonstrates a very practical application of a design tool that is generally considered highly academic. The project also demonstrates the use of combining instrumentation and FEM analysis in expediting the safe construction of complex structures where more conventional analytical methods fall short.

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