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Back Analysis of an Elliptical Shaft for the Texas Superconducting Super Collider Project

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ABSTRACT: This paper focuses on the back analysis of an elliptical shaft using the finite difference numerical modeling approach. The back analysis was performed based on an initial understanding of the rock mass response to excavation, developed through analysis of field instrumentation data. The instrumentation program consisted of measurements of lateral deformation, heave and pore pressure within the undoweled and predoweled reaches of the advancing shaft. The field measurements point to a blocky, post-peak response of the clay shale beneath the advancing shaft invert, and indicate the importance of predoweling reinforcement in controlling progression of the blocky failure. In addition, the technique developed for simulating the impact of the blocky, post-peak response of the shale on the redistribution of stresses around the shaft opening was successful in describing the pore pressure response beneath the shaft invert and has proven to be a useful tool in studying the redistribution of stresses in blocky materials.

1 INTRODUCTION

Clay shales are materials that engineers and geologists have a difficult time classifying as strictly rock or strictly soil, and are often termed soft rocks or highly cemented clays. For designers, predicting the response of this "in-between" material to staged shaft and tunnel excavation can be challenging. One example of this type of challenge was the N15 Magnet Delivery Shaft (N15-MDS), which was designed and constructed for the Superconducting Super Collider (SSC) project in Waxahachie, Texas. The N15-MDS excavation bottomed in the Eagle Ford Shale formation. The Eagle Ford Shale is classified as a very low strength (UCS 2 MPa), dark gray to black, calcareous to noncalcareous clay shale. The low strength and high clay content (>95% passing the minus No. 200 sieve, with approximately 49% of the clay fraction being montmorillonite), combined with significant calcium carbonate binder (9%) and a degree of saturation of 100%, all served to add even more complexity to the behavior of this material during excavation. Due to the complex behavior of the Eagle Ford Shale, two methods for analyzing the deformational response of the shale during construction were considered. Effective stress analyses were performed to investigate the appropriateness of each method, and field measurements of deformation and changes in pore pressure during excavation were used to examine the validity of the proposed mechanisms.

2 SHAFT CONFIGURATION

The N15-MDS is an elliptical shaft, approximately 9 m x 18 m in cross-section from the ground surface to a depth of 58 m; changing to an ellipsoidal shaft from that point to the bottom of the shaft at a depth of 73 m (Figure 1). Starter and tail tunnels for tunnel boring machine staging and assembly tie into the shaft in the northwest and southwest "corners" of the ellipse. The elliptical shaft configuration was required to ensure proper handling of the superconducting magnets during installation.

The N15-MDS project specifications mandated continuous rock dowel and shotcrete support. In addition to the rock dowel support required for the walls of the shaft, the design called for predoweling the Eagle Ford Shale beneath the shaft invert. The predoweling was to be performed while the advancing excavation was still in the much stronger Austin Chalk formation above the shale. The predoweling scheme was developed to control deformations beneath the shaft invert, and to help maintain the integrity of the shale until the final 3 m thick concrete shaft invert was completed. The predoweled zone beneath the shaft consisted of approximately 100, 15 m long, No. 11 steel bars grouted at the bottom of 30 m long vertical and subvertical holes drilled from the base of the shaft's lower liner key at a depth of 58 m.

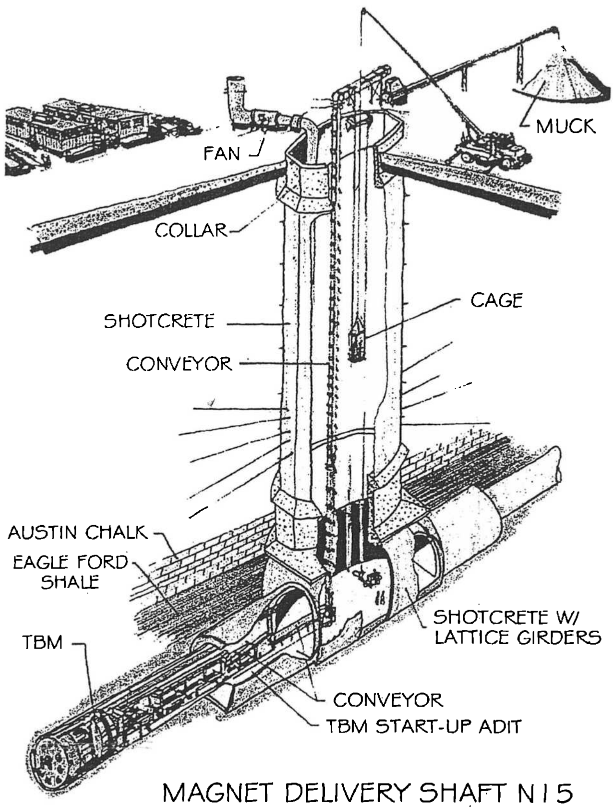

Figure 1. Artist Rendition of Various Components of the N15 Magnet Deliver Shaft (N15-MDS)

3 GEOLOGIC SETTING

Boring log data for the shaft developed in the geotechnical investigation for the shaft indicates that residual clay soil with weathered limestone fragments extends from a depth of 0 to 0.3 m. The residual clay is underlain by soft to medium tan weathered limestone of the Austin Chalk formation to a depth of 3.6 m. A sharp contact to the fresh, medium to moderately hard, gray Austin Chalk is present at 3.6 m, and the fresh limestone extends to a depth of 60.6 m. The last approximately 1 m of Austin Chalk varies considerably from the host material and consists of extremely argillaceous limestone with abundant fishbone fragments and other fossil debris. Locally this zone is termed the "Fishbed Conglomerate." Below the Fishbed Conglomerate lies the Eagle Ford Shale, which extends beyond the bottom of the excavation to a depth of 152 m.

Mechanical and index properties used in the back analysis for the Austin Chalk and Eagle Ford Shale are summarized in Table 1. The properties are based on laboratory and in-situ test results produced during geotechnical investigations for the SSC project.

Table 1. Back Analysis Input Parameters

Design Parameters	Units	Austin Chalk	Eagle Ford Shale
1. General Characteristics			
Dry Unit Weight	kN/m^3	19.5	18.4
Total Unit Weight	kN/m^3	22.0	21.3
Porosity		0.24	0.32
2. Effective Stress Strength Parameters			
Cohesion (c)	Pa	4.544e6	2.345e5
Friction Angle (ϕ)	deg	30	12-20
Tension Cut-off	Pa		1.381e5
3. Deformation Characteristics			
Effective Stress Conditions:			
Bulk Modulus	Pa	1.760e9	2.316e8
Shear Modulus	Pa	1.265e9	1.990e8
4. In-situ Stresses - Ko Ratio			
Maximum (direction)		2.1(N35E)	1.5(N18E)
Minimum (direction)		1.5(N55W)	1.5(N18E)
5. Permeability			
Parallel to Bedding	cm/s	5e-7	1e-8
Normal to Bedding	cm/s	5e-8	1e-9

4 GEOTECHNICAL INSTRUMENTATION

Figure 2 is a plan view of the instrument locations at the N15-MDS site. Instruments installed from the ground surface prior to shaft excavation included four vibrating wire piezometers (designated P1, P2, P3 and P4), two pneumatic piezometers (designated PP1 and PP4) and four inclinometers (designated MDS-1 to MDS-4). The instruments shown inside the shaft (i.e. piezometers P5-P8 and heave gages HG1-HG2) were installed from within the shaft at the base of the shaft's lower liner key.

Locations and depths of the piezometers, convergence anchors and multiple position borehole extensometers (MPBXs) are presented in the profile of the shaft instrumentation in Figure 3.

The piezometers were spaced vertically to ensure an accurate understanding of the groundwater response to the shaft excavation. This included one piezometer in the Austin Chalk above the Bentonite Marker Bed, and two in the Austin Chalk below the bentonite but just above the Eagle Ford Shale contact. The three remaining piezometers installed from the ground surface were spaced vertically within the Eagle Ford Shale, just outside the perimeter of the ellipsoidally shaped shaft bottom.

When shaft construction had progressed to a depth of 58 m (approximately 3 m above the Austin Chalk/Eagle Ford Shale contact) excavation was discontinued for a period of 19 days in order to finish construction of the shaft's lower liner key. From this point, the contractor was required to predowel the invert of the shaft (from the planned shaft bottom to approximately 15 m below the invert) and to

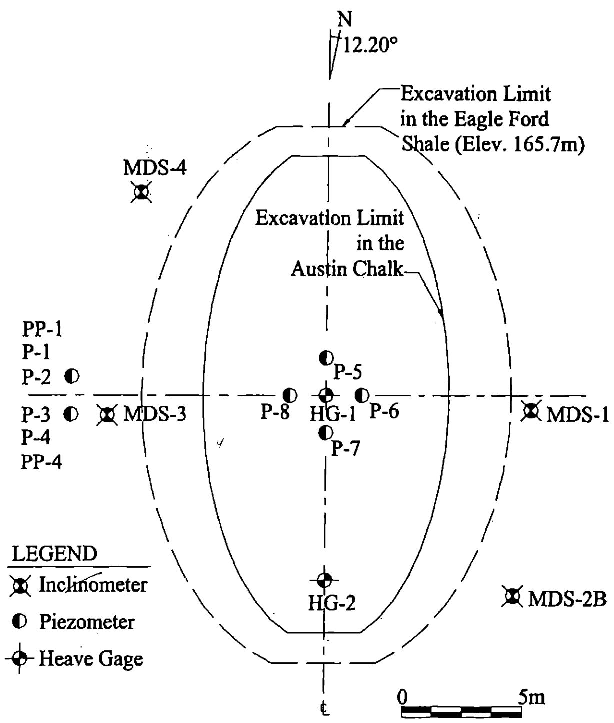

Figure 2. Plan View of the Instrument Locations at the N15 MDS Site

drill holes for installation of the two heave gages (HG-1 and HG-2) and the four additional vibrating wire piezometers (P5-P8). These instruments were to be used to measure the heave and pore pressure response of the shale, directly beneath the shaft, as the excavation progressed.

5 RESULTS OF INSTRUMENTATION

From the recorded displacement and pore pressure instrumentation data, an initial understanding of the rock mass response to excavation was developed.

During excavation in the Austin Chalk, displacements around the large elliptical shaft opening were recorded along with a drop in the piezometric level around the shaft as the excavation progressed. Measurable deformations were not recorded in the Eagle Ford Shale until the shaft excavation was less than one meter above the Austin Chalk/Eagle Ford Shale contact. At that point, both inclinometer and heave gage readings revealed that the shale had begun to respond to the approaching excavation. As the excavation progressed through the contact and into the shale, the piezometers beneath the shaft invert recorded a significant drop in the pore pressure beneath the shaft (Figure 4).

The inclinometers revealed a "stepped" pattern of horizontal deformation in the undoweled shale below the contact, and the heave gage data suggested that the "brittle," undoweled shale was yielding and separating into blocks as the excavation progressed (Figure 5).

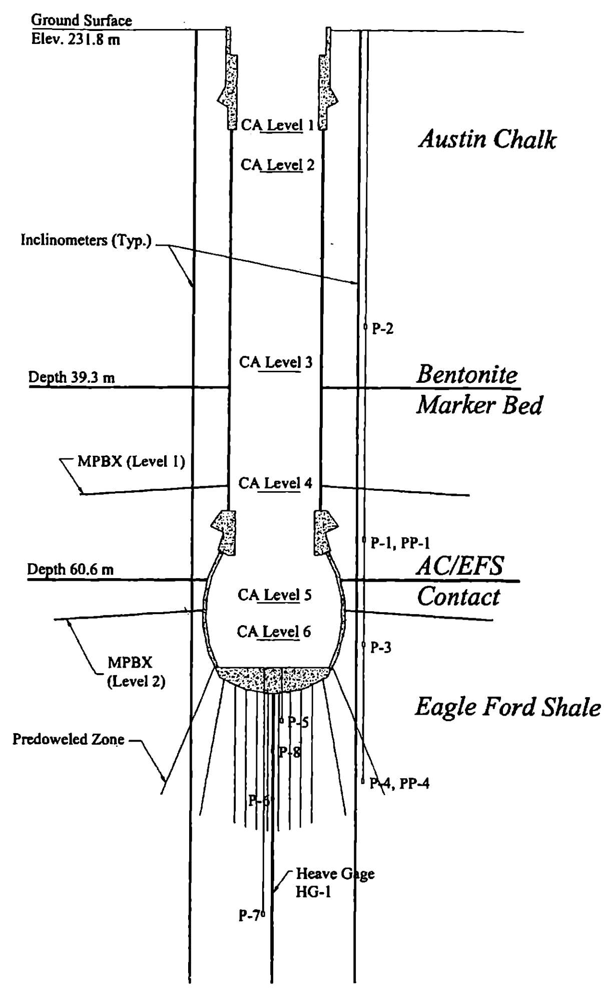

Figure 3. Profile of N15-MDS Shaft Instrumentation

The predowels in the shaft invert appeared to prevent the mechanism of blocky failure from developing, and served to control deformations and maintain the integrity of the shale beneath the invert until the excavation progressed to within 4 m of the final shaft invert. At that point, portions of the predowels failed and the mechanism of blocky failure extended down into the predoweled zone beneath the invert. Failure of the dowels in the top 3 m of the predoweled zone resulted in blocks of shale moving up and through the predoweled zone (Teetes and Mrugala 2002).

6 NUMERICAL MODELING APPROACH

Undrained, effective stress models were used to investigate the ability of the effective stress approach to predict the ground and pore pressure response of the Eagle Ford Shale.

The numerical modeling was carried out using the 2D finite difference code FLAC (Fast Lagrangian Analysis of Continua) developed by the Itasca Consulting Group (Itasca 2000).

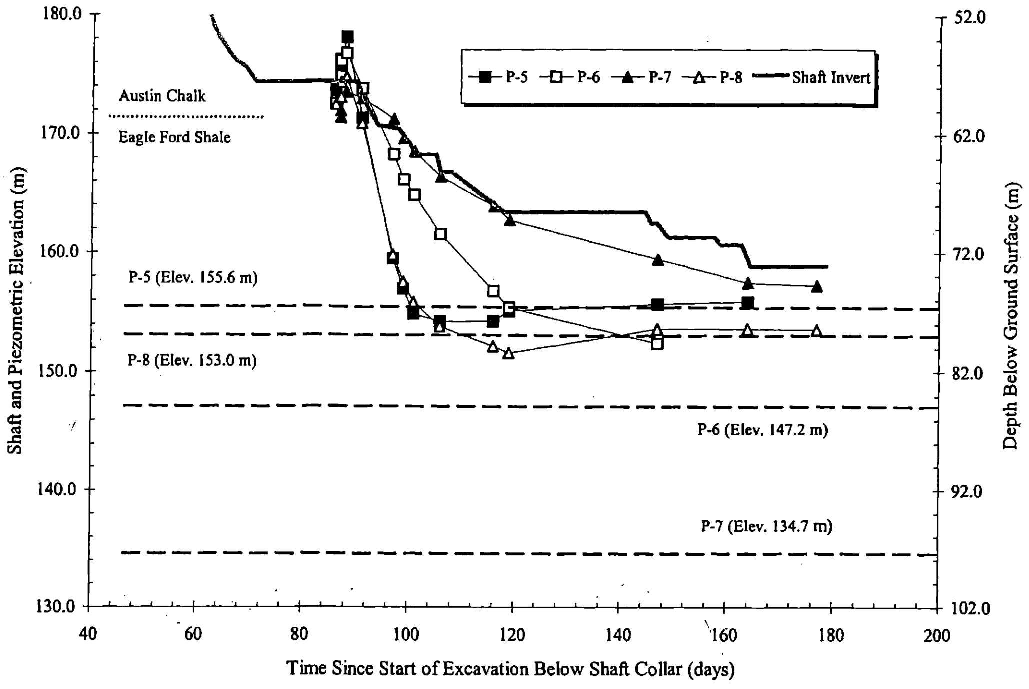

Figure 4. Piezometer Readings Beneath the Shaft Invert at the N15-MDS Site, adapted from Shannon & Wilson 1993

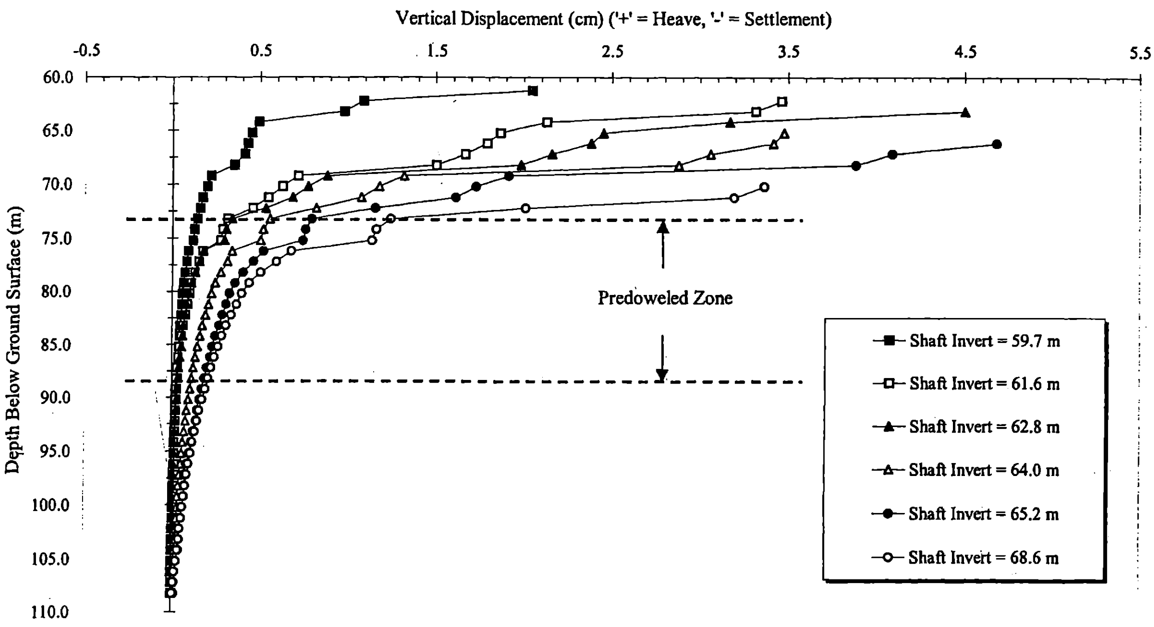

Figure 5. Heave Gage (HG-1) Readings at the N15-MDS Site, adapted from Shannon & Wilson 1993

In the analysis, the rock mass was discretized using a finite difference grid of 34 by 61 zones, representing a 230.4 m wide by 231.8 m deep section. These dimensions were chosen based on the results of sensitivity analyses aimed at determining the impact of the boundary conditions on model predictions.

To represent the equivalent circular shaft radius in the axisymmetric model, an average axis radius of the ellipse was used (i.e., radius = (a + b)/2). The variable shotcrete thickness in the shaft and the thickness of concrete in the shaft collar were incorporated into the discretized mesh as well.

The Austin Chalk was modeled using an elastic, isotropic model with constant stiffness. In contrast, four different constitutive models were used in an attempt to describe the Eagle Ford Shale response. First, an elastic, isotropic model with a constant stiffness; second, a Mohr Coulomb plasticity model with the shear yield surface corresponding to a Mohr Coulomb criterion, and either dilatant or non-dilatant post-peak behavior; third, the isotropically hardening/softening elastoplastic Modified Cam

Clay model; and fourth, the same Modified Cam Clay model but with yield described via a Hvorslev strength criterion.

6.1 Modeling Methodology

Two methods for analyzing the deformational post-peak response of the shale observed during construction were considered. In the first, "conventional" method, excavation of the shaft was based as closely as possible on the actual construction sequence and focused on the ability of each of the four chosen constitutive models to predict the response of the shale. In these analyses, the model simulation consisted of excavation of the shaft collar to a depth of approximately 11 m, followed by 39 excavation stages, ranging from 1.0 to 2.2 m each, to the bottom of the shaft at a depth of 73 m.

In the second method, a technique was developed to replicate the impact of the blocky failure on the redistribution of stresses beneath the shaft. The instrumentation data suggests that failure and fragmentation of the Eagle Ford Shale occurred as the shaft excavation progressed through the Austin Chalk/Eagle Ford Shale contact and into the brittle, over-stressed, undoweled shale beneath the contact. Based on the progression of the blocky failure captured in the instrumentation data, the excavation sequencing was modified. The simulation proceeded as described above, until just above the Austin Chalk/Eagle Ford Shale contact. The modified simulation then involved the removal of the last zone of Austin Chalk above the contact and the replacement of the first four zones of undoweled Eagle Ford Shale with an applied vertical stress equivalent to the weight of the removed zones. The next step was a repeat of the first, with the remainder of the undoweled shale being removed and a vertical stress representing the remaining zones being applied to the shaft invert, and in effect, simulating the progression of the blocky failure. The final step in the model involved removal of the remaining applied vertical stress, and replacement of the stress with zones representing the final concrete shaft invert.

7 BACK ANALYSIS RESULTS

The numerical modeling results using the "conventional" method indicate that each of the four constitutive models, to varying degrees of accuracy, is able to predict the displacements occurring around the elliptical N15-MDS. However, none of the four constitutive models chosen to describe the shale behavior were capable of capturing the blocky, post-peak mechanism of shale failure and the corresponding drop in pore pressure beneath the shaft (Figure 6).

In contrast, Figure 7 presents the pore pressure prediction beneath the shaft developed utilizing the modified simulation. The results indicate that the technique is capable of replicating the post-peak mechanism of shale failure and the corresponding redistribution of stresses around the shaft responsible for the large drop in pore pressure recorded in the field.

Although the predicted trends are accurate and variability in the magnitude of the pore pressure response with depth is reproduced, the magnitude of the final predicted response at the P-5 and P-8 piezometer locations may be exaggerated. The reader should note, that in an effort to better numerically evaluate the entire pore pressure response beneath the shaft, the water was given a high tension limit value in order to prevent cavitation from occurring in the model.

8 CONCLUSIONS

Though the constitutive models used in the back analysis were capable of predicting displacements around the shaft, they were incapable of successfully predicting the post-peak, blocky behavior of the shale and the resulting pore pressure response.

Failure in the Eagle Ford Shale was due primarily to the low shear strength of the cemented clay shale relative to the range of stresses encountered. In the field, failure occurred along bedding planes and other planes of weakness resulting in the blocky invert conditions, which were captured in the instrumentation data and described herein. Given the blocky, post-peak response, the pattern of stress redistribution was directed further ahead of the excavation, resulting ultimately in the progression of the blocky failure into the predoweled zone. The removal of the Austin Chalk, the subsequent failure of the undoweled shale, and the resulting change in the state of stress around the excavation combined to create the drop in pore pressure that was recorded at the four piezometers beneath the shaft.

The back analysis results indicate that mechanistic application of a simple best-fit computer model to predict ground response may lead to serious misconceptions regarding the mechanism of ground behavior. In addition the results indicate that the technique developed for simulating the impact of the blocky, post-peak response of the shale on the redistribution of stresses around the shaft opening was successful in describing the pore pressure response beneath the shaft invert, and has proven to be a useful tool in studying the redistribution of stresses in blocky materials. Pore pressure data was used to substantiate the appropriateness of the back analysis approach, and clearly indicates the importance of an effective stress analysis in providing a rational explanation of the behavior of saturated soft rocks.

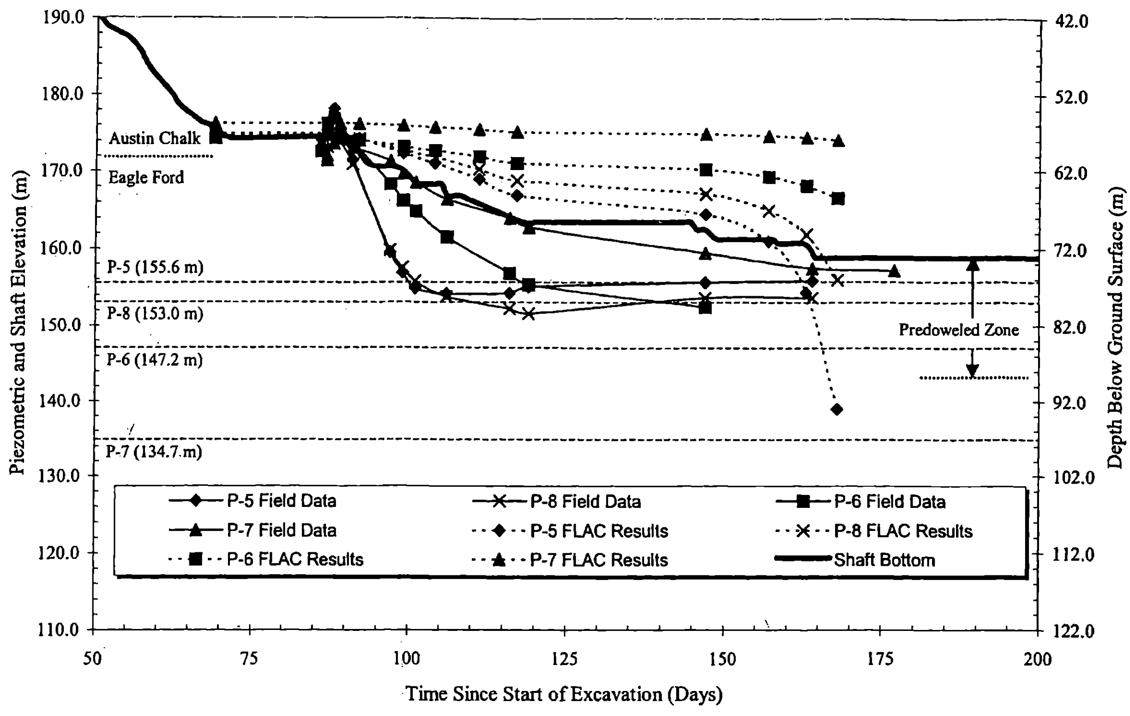

Figure 6. Pore Pressure Prediction using Conventional Construction Sequencing Approach

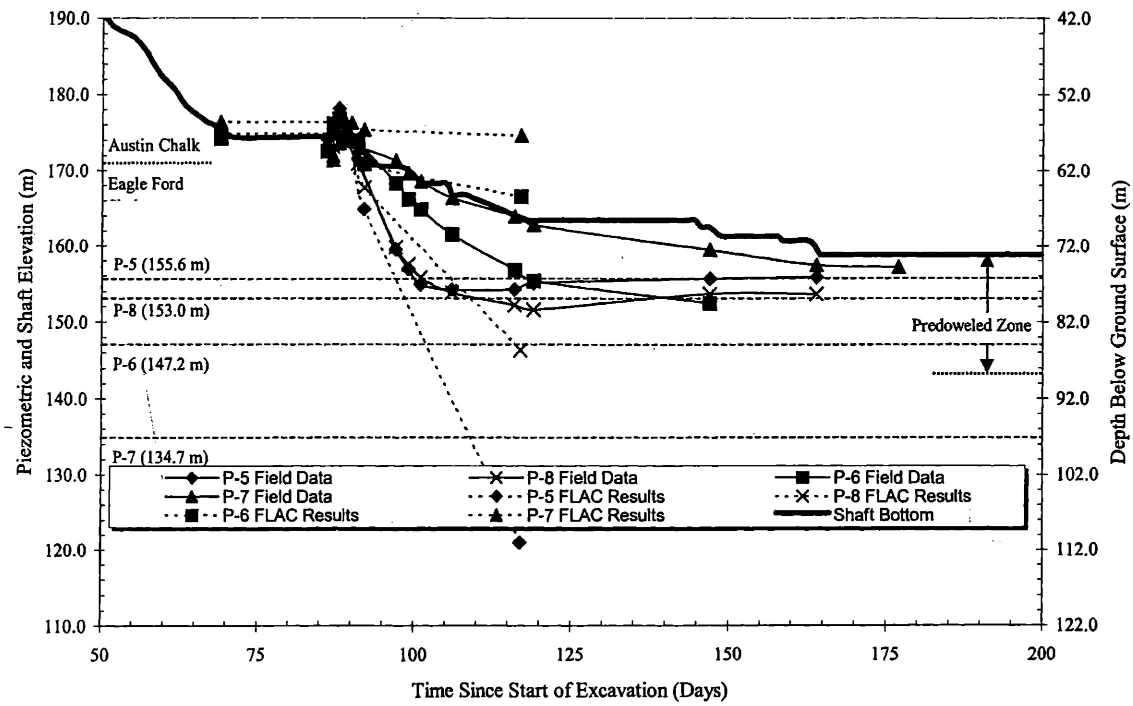

Figure 7. Pore Pressure Prediction using Technique to Simulate Blocky, Post-Peak Response of the Shale

ACKNOWLEDGEMENTS

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