ROADWAY PERFORMANCE IN AN EXPANSIVE CLAY

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Abstract

The performance of three pavement designs with expansive clay subgrade is presented. The pavements have been subjected to extensive warping attributed to differential swelling of the underlying soil. The purpose of this paper is to evaluate the effectiveness of the three designs in reducing warping, and provide suggested alternative designs.

The study focuses on pavements west of Dallas, Texas situated over weathered shale of the Eagle Ford geologic formation. The weathered shale is highly expansive with heaving in excess of 12 inches being recorded. Postconstruction heave is attributed to increase in the soil moisture regime over time.

Pavement warp occurs primarily in deep cut areas where the finished grade lies near or below the original zone at which soil moisture was stable and not influenced by seasonal fluctuations. Data indicate the overall movement of the pavements studied was upward. Differential vertical movements caused warping. The differential movement is attributed to the influence of: underground utilities; micro and macro soil structure features; drainage; patterns of water migration; and stress release.

The study evaluates the performance of three specific pavements. Subgrade treatments used to minimize potential movements included, removal and replacement with lime stabilized soils and inert fills, and maintaining positive drainage.

Alternative subgrade treatment by preswelling is discussed. Modification of pavement shoulders and base to account for shrinkage and loss of bearing support (is a necessary component of preswelling design. Preswelling and suggested base and shoulder modifications are compared to current design techniques used in the area on an economical basis.

INTRODUCTION

Warped pavements founded on expansive clays often result in extraordinary maintenance costs being experienced much sooner in the pavement life than anticipated. Even if the effect of warping is not serious enough for repair, its effect on vehicle operations does little good for the reputation of pavement designers and highway contractors. Warped pavements founded on plastic clays present an opportunity for soils engineers. Warping as used in this paper is a term applied to a phenomena caused by differential expansion of the pavement's underlying soils. Soil expansion causes a roller coastering effect or series of successive waves which extend across the pavement section. By comparison, surface depressions caused by shrinkages are generally limited to the outside edges of the pavement and do not extend across the entire width as is the case of expansion of underlying joints. For relatively thin pavement sections, failure can occur in either case as a result of loss of continuous subgrade support. Shrinkage can be and has been effectively controlled by the addition of either vertical or horizontal barriers (1, 2, 3, 4,) and/or by the extension of the pavement shoulders (2, 4). Little attention has been given to controlling expansion with its resultant warping effect of pavement.

This paper reviews pavement design and performance in a specific geologic formation, the Eagle Ford, whose outcrop residual soils are prone to swelling. It is based on general observation of pavement performance throughout the local area and on evaluation of three sites west of Dallas, Texas. An example of pavement movement in this formation due to heave is shown in Figure 1. The information and recommendations herein are considered to be applicable in varying degrees to other expansive soils derived from other parent geologic formations.

GEOLOGIC DESCRIPTION

The Eagle Ford Group is a marine deposited montmorillonitic clay-shale of Cretaceous Age. Weathering of the formation results in relatively dry, thick, deep, potentially expansive clays. Depth of weathering typically varies from ten to 35 feet. Surface movements in excess of 12 inches have been documented by the author based on survey data (5).

The weathered shale within the study area exhibits the horizontally bedded structure characteristic of the shale, and is moderately to highly jointed and fissured. The soil fabric is very dense and relatively impermeable; however, the mass permeability is greater due to the joints and fissures.

The moisture content of the soil below the zone of seasonal moisture variation is generally two to four percentage points below the plastic limit and becomes drier with depth. Samples subjected to Constant Volume Swell (CVS) tests exhibit swell pressures on the order of ten to 15 ksf and volumetric swell of ten to 15 percent. A typical soil moisture profile with pressure swell test results is shown in Figure 2. The zone of seasonal moisture variation is relatively shallow approximately 7 to 10 feet below surface. The shallowness is attributed to, among others; rolling site topography which enhances surface drainage, and the propensity of the surface soils to swell and decrease their permeability. The jointed and fissures structure may also contribute by inhibiting soil suction between adjacent soil blocks.

Perched groundwater is intermittently present in varying degrees along the weathered/unweathered interface. Perched groundwater is attributed to surface infiltration, gravity flow through joints and fissures, and then along weathered patterns. Subsurface channelization is not uncommon, and coupled with the intermittency of the perched groundwater, can make prediction of the hydro-geologic conditions difficult.

ACTIVE ZONE OF MOVEMENT

The active zone is defined as the soil column measured from the surface, which is subject to potential movement. It extends well below the zone of seasonal moisture variation, and frequently is in excess of 20 feet. This depth of active soils is considered to be a result of the high swell pressure and volumetric swell characteristics exhibited throughout the soil or weathered profile. An active zone to this depth is not unique to the Eagle Ford with depths in excess of 20 feet reported by both Johnson (6) and Komornick (7) in other formations.

The concept of the deep active zone, and zone subject to seasonal moisture variation is shown in Figure 2. The swell pressure for the upper soils is seasonally variable dependent on soil moisture; whereas below the seasonal zone, the swell pressures of clay shales can be above the available gravity stresses for significant depths.

An awareness of the full potential active zone is necessary if an accurate prediction of surface movement is to be made. The concept of a seasonal zone underlain by a deeper active zone is also important from a design aspect. For example, if free water is introduced relatively deep (15 to 20 feet) from a utility trench system, the resultant swelling will be reflected in pavement warping at the surface.

LITERATURE REVIEW

Several excellent sources are available which treat the subject of roadway design over expansive clays with respect to broad concepts (1, 2, 8). Based on the literature, the following items appear to be common to clayey, shrink-swell formations:

1. An increase in soil moisture in unsaturated clays occurs immediately beneath the center of the pavement over time. Among the causes attributed to this rise is a reduction in evapotranspiration, changes in temperature and surface water ingress through joints and cracks in the pavement.

2. Shoulders and pavement edges, if unprotected, will reflect cyclic movement (shrink-swell) associated with seasonal variation in soil moisture.

3. Removal of a limited depth of expansive clay and replacement with inert fill in formations where the active zone extends to substantial depths is not effective if water is made available to the underlying clay (1, 2, 8).

4. The use of permeable soil as backfill for utility lines can result in heave due to swelling of the underlying and adjacent clays since the permeable fills can become a conduit for free water to the deeper or adjacent clays.

5. Altering the groundwater regime can initiate deep seated movement.

6. The use of thick pavement sections to act as a surcharge is generally not effective over soils exhibiting high swell pressures (2, 7). Thicker sections can, however, spread the movement over a greater distance.

7. Moisture barriers, either horizontal or vertical, are effective for stabilizing soil moisture, provided complete cutoff of water can be obtained (3, 4).

8. Pre-wetting the subgrade has been effective in reducing postconstruction movement (1, 2, 9, 10, 11).

This list is far from exclusive. However, it enumerates some of the common factors involved with roadway design over an expansive soil.

The methods for design in clays exhibiting high swell potentials can be effectively divided into two philosophies, wet or dry, dependent upon the condition of the subgrade prior to placement of the pavement. The dry approach requires the postconstruction maintenance of moisture conditions existing at the time of placement, i.e., the use of either horizontal or vertical barriers. The wet approach alternatively styled "pre-swelling", attempts to elevate the subgrade moisture prior to placement of the pavement.

The amount of water needed to effectively "pre-swell" the clays is definable through evaluation of the soil properties. A technical explanation is beyond the scope of this paper. For general purposes, it can be assumed the amount of water added will be the amount needed to bring the moisture content two to four percent above the clays' plastic limit.

Suggested pre-swelling techniques consist of delaying construction through the rainy season (11), ponding (1, 2, 10) and pressure injection (9). Postconstruction heave control by lime slurry pressure injection was reported by Cothren (9), although the pavement was only two years old at the time of the report.

CASE STUDIES

Pavements constructed by City, County and State Agencies and private developers within Dallas County, Texas underlain by outcrops of the Eagle Ford Group have experienced warping to varying degrees. These areas are generally limited to locations where cuts of varying amounts were required to establish finished grade.

Cursory examination of pavement performance at 12 locations indicated the unaffected areas were situated in either deep fill sections, very deep cut sections, or underlain by varying thicknesses of alluvial or terrace deposits. Lack of movement in the areas of very deep cuts is attributed to the exposure of the unweathered shale as a subgrade soil.

In order to provide more specific information, three sites were chosen which incorporate different design sections. Each of the three locations were evaluated as to exposed geologic conditions, the number of individual warps per length of roadway, drainage, cut or fill conditions, presence of underground utilities, and the design section. A summary of the evaluated items for each site is provided in Table 1. More detailed information on each site is provided in the following paragraphs.

Site 1: Farm to Market 1382, Cedar Hill

This section of Farm to Market (FM) 1382 studied consists of the relocation portion around the recently completed Joe Pool Lake, southwest of Dallas, Texas.

The design used for both cut and fill sections is shown in Figure 3. No utilities are shown on the plans in the affected area studies, nor were any observed on site. All of the warping occurred in cut sections. Good drainage of surface water appeared to have been established and maintained by the use of bar ditches.

Individual warps and warps in groups of 2 and 3 were observed. The differential movement extended across the width of the pavement, with the length of effected pavement being 35 to 60 feet, and differential movement of three to six inches. Typically, differential movement was greater towards the uphill side of the original grade. A transverse pavement crack was present along the center of the high elevation of approximately one-half of the observed warps.

Based on the general transverse nature of the warp, subgrade heave is attributed to perched water traveling through the joints and fissures of the weathered shale and/or through the weathered limestone used as a base. As to the design, no special precautions were taken to account for a swelling subgrade or the naturally complex hydro-geologic conditions compounded by construction operations.

Site 2: Westbound Interstate Highway 635, Immediately East of MacArthur Boulevard, Irving, Texas

The warping at this site consisted of 20 individual warps over a 1.5 mile length of roadway. The length of warps varied from approximately 50 to 100 feet, with differential vertical movement of three to six inches. The roadway is approximately seven years old and has experienced distress at this location since construction. The design section is shown in Figure 4.

Project plans indicate cuts of 12 to 27 feet were required to establish grade. Borings indicate the top of the unweathered shale is at a depth of about 40 feet. Utility lines are not shown to be present under the roadway. Positive drainage of surface water away from the pavement was provided.

As shown in Figure 4, special precautions in the form of over-excavation and replacement were taken in the design to account for the presence of expansive Eagle Ford clays. Overexcavated sections were replaced by 36 inches of non-expansive fill. Examination of Figure 4 shows that the fill was extended beyond the surface of the roadway and shoulders.

Based on the design section, the soils encountered at a nearby outcrop, and the amount of cut required to establish grade, subsurface conditions at the completion of excavation consisted of varying thicknesses of weathered shale. Since construction, the clays (weathered shale) have expanded due to the availability of water. It is anticipated water is made available both by surface runoff infiltrating the sandy subbase, and by perched groundwater flowing along pre-existing weathered channels.

The pavement warp here is attributed to moisture infiltration into the subgrade clays and subsequent differential expansion. The warping is not considered to be a result of the seasonal variation in moisture because of the relatively wide shoulders which provide a horizontal barrier, and because the warping extends across the width of the pavement.

Site 3: MacArthur Boulevard, North of Interstate Highway 635, Irving, Texas

MacArthur Boulevard consists of an eight-inch concrete pavement over a modified subgrade. Subgrade modification consisted of a single, three-foot deep lime slurry injection, with scarification of the surficial lime into the upper six inches of subgrade. Utilities are present under the pavement. The utilities were encased in concrete, with native clay soils used as backfill. Utility lines parallel and adjacent to the eastside of the pavement were bedded in gravel and backfilled with a clayey sand. The design section is shown in Figure 5.

Movement of the pavement since project construction is shown in Figure 6. Within the portion of the roadway underlain by residual soils, measured movements have ranged from 2.0 to 11.5 inches. Movements shown in Figure 6 were measured along the east gutter line, but similar movements were measured 11 feet west of the east gutter. As at Sites 1 and 2, the observed warping extended across the width of the pavement.

The proximity of the warps to existing utility lines is evident in Figure 6. Observations over the last four years have shown a progressive extension of the warping from the east to west.

Two soil borings were made through the roadway at the location of a heave immediately underlain by a utility line. These borings encountered perched water in the backfill clays, and an elevated soil moisture in the adjacent natural soils. Based on the borings and subsequent utility excavation, it is believed the native clay backfill was placed in a dry condition in the form of small clods. Water traveling in the gravel bedding and sand backfill of a nearby utility line adjacent to the uphill side of the pavement (east) flowed through the backfill of the utility line beneath the pavement, and became accessible to the relatively dry natural clays both below and adjacent to the excavation.

ALTERNATIVE DESIGN CONSIDERATIONS

Alternative designs must answer two basic questions; will the design perform acceptably, and is the cost/benefit ratio acceptable. Cost/benefits were analyzed by comparing a typical section used in the Dallas area for a particular section versus the sections currently used in the Eagle Ford geologic formation.

Analysis of the costs associated with construction of a section of heavy highway were analyzed by comparing a section used for I-635 West of I-35E (Site 2) to another section of I-635 East of I-35E. The section of I-635W West of I-35E is shown in Figure 4. The design section for I-635 East of I-35E consists of eight-inch thick concrete, over a six-inch thick lime stabilized low Plasticity Index imported fill (PI 6 to 15) over a six-inch thick lime stabilized (three percent) subgrade. A comparison of the costs associated with construction of these two sections is presented in Table 2. The I-635 section, west of I-35E costs approximately $41.75 per square yard compared to $26.35 per square yard east of I-35E, for a cost differential of $15.40 per square yard. Neglecting the cost of extraordinary maintenance for warped sections of alternative designs resulting in pavement costs less than $41.75 appear to be reasonable.

Costs associated with thinner sections were evaluated using a collector street of standard design (eight inches of concrete over six inches of six percent lime stabilized subgrade) as a base. This section costs, in the Dallas market, approximately $22.45 per square yard. Removal and replacement, a typical method used to correct excessive warping, is estimated to cost $30.00 per square yard. Considering the replacement costs, some additional expenditures could be economically supported at the time of construction if it would preclude repair later in the form of removal and replacement. Conservatively, approximately ten percent of the concrete pavements situated on the Eagle Ford formation are replaced over a 20 year period in the Dallas area.

As previously discussed, there are two design philosophies considered to be applicable in this geologic formation; wet or dry. The wet philosophy is to pre-swell a portion of the active zone prior to placement of the base and pavement. The dry approach consists of maintaining the existing soil moisture below the pavement structure. Due to the depth of the active zone and high volumetric swell, complete removal and replacement of the soil with less active or inert soils is not considered feasible.

If a dry approach is to be used, the barriers to subgrade water must account for the complex hydro-geologic of the site as well as obvious man-made features and environmental changes imposed by development. Perched, intermittent groundwater is frequently encountered at the interface of the weathered/unweathered shale. Seepage occurs through both macro and micro discontinuities, and follows the pattern of weathering, which does not always follow surface topography.

Intermittent groundwater made available to subgrade clays which have heretofore been dry, or which have reduced stress associated with cuts, will swell.

Utility lines backfilled with permeable soils provide an obvious source of water transmission. Use of impermeable backfill while essential may not stop the availability of water. Impermeable backfills perpendicular to the gradient of perched water can impede flow, building up higher gradients, or force the water to travel through other discontinuities, either of which could provide water to relatively dry subgrades.

Alternatives such as clay backfill in utility lines under roadway sections, and/or incorporation of subsurface drain systems down gradient of the roadway may be beneficial. The most important factor, if the dry approach is to be successful, is to account for all sources of potential water. As seen in the three study sites, and based on the author's experience with both paving and structures in this formation in the Dallas area, successful application of a dry approach is difficult.

Thicker pavement sections can reduce the effect of the warping by spreading the differential movement over a greater horizontal distance. As evidenced by pavement performance at Site 2, however, even relatively thick sections have not proven effective. Partial removal of the clays immediately under the pavement section and replacement with non-expansive clayey sands is not recommended. Ponding of water in the more permeable clayey sands above an underlying clay must be prevented, or deeper movements will occur.

The wet approach consists of pre-swelling the subgrade prior to construction of the base or pavement. Pre-swelling by ponding has been effectively used in this and other formations (1, 2, 10, 11). Postconstruction shrinkage can then be effectively controlled by installation of either horizontal or vertical barriers.

Difficulties associated with ponding consist of the time involved, the extremely wet surface at the completion of ponding and the problem of getting deep penetration of the water. The use of the post holes in conjunction with ponding is a variation which can aid faster penetration of water to deeper depths. The post holes must; however, be sealed at the completion of ponding operations unless successful swelling throughout the active zone was accomplished, in order to control the availability of additional water to the deeper zone. Otherwise, available water can result in postconstruction heave at depths below previously swelled soils.

A suggested alternative to ponding consists of deep multiple pressure injections. The injections may consist of either water with surfactant coupled by a surface seal or a combination of lime slurry, and water injections. The purpose of the lime injection is to provide a surface seal to maintain the injected moisture during the construction phase prior to placement of the base and wearing surface. Multiple water injections are necessary in order to provide free water in the joints, fissures and hydraulic fractures for absorption by adjacent clays. Time between injections must be allowed for absorption and swelling to occur. The time interval is considered to be dependent upon the clay structure and the spacing of joints and fissures, but is generally two to four days. Three to five injections are typically necessary to sufficiently pre-swell these soils.

(The lime slurry pressure injection industry contends an increased strength and a reduction in moisture migration is obtained by multiple lime slurry injections. This point is not debated one way or the other. However, the main benefit of pressure injection in this geologic formation is considered, to be one of pre-swelling by induced moisture.)

The depth of injection is dependent upon the desired reduction in potential movement, but generally varies from three to ten feet. The author personally prefers the deeper injections.

An alternative, subgrade treatment for a city street (eight inch pavement) incorporating pre-swelling consists of one lime followed by three water injections to a depth of eight feet. This subgrade treatment adds approximately $2.00 per square yard or pavement to the costs previously sited ($22.45).

An alternative heavy highway design incorporating preswelling is shown in Figure 7. The savings of this section compared to the section used for I-635 (Site 2) amounts to $7.86 per square yard.

Preswelling by injection under roadways has not been extensively addressed in the design community. Part of the lack of use of this technique is attributed to the mysticism associated with the injection process. The author can add that the preswelling process has been used under building slabs in this formation for over 12 years, with a high degree of success. The use of dry techniques, removal and replacement and/or installation of horizontal or deep vertical barriers has not been successful, with results not unlike the roadways observed.

CONCLUSIONS

Based on the preceding case histories and discussions, the following conclusions are presented:

1. Soils of the Eagle Ford geologic formation within the Dallas area ause warps in pavement due to differential swell.

2. None of the pavement designs in the Dallas area reviewed effectively controlled pavement warp.

3. For the dry approach in design, all potential sources of water must be considered and positively controlled during and after construction.

4. Preswelling, based on previous work by others on roadways and by the author under buildings in this formation, appears to be a viable solution. Preswelling via post hole and ponding and by multiple injections have performed satisfactorily.

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TABLE 1

OBSERVATION SITES AND ROADWAY PERFORMANCE

Site Number	Number of Warps/ Length (Mile)	Drainage Conditions	Cut or Fill	Utilities	Approximate Age (years)	Comments
F.M. 1382	15/2.1 (Southbound) 17/1.3 (Northbound)	Drained away from pavement non-irrigated	cut	None	6	Section presently being overlaid w/asphalt
MacArthur Blvd.	6/0.20	Controlled construction grade/ surface drained to pavement Irrigated	cut	Numerous/w special backfill detail	4	2 panels replaced
I-635	10/0.50 (Westbound) 20/1.50	Drained away from pavement non-irrigated	cut	None	6-7	Section replaced and overlain

TABLE 2

SUMMARY OF COSTS, HEAVY HIGHWAY SECTIONS

Item	Cost/Sq. Yard
9 inch concrete pavement	$ 23.00
4 inch asphalt stabilized base	$ 9.95
36 inches of imported fill, including excavation, PI between 4 and 50	$ 8.80
Total approximate cost I-635 section comparable to Fig. 4	$ 41.75
Section 2, I-635, East of I-35E	
8 inch concrete pavement	$ 20.00
6 inch lime stabilized imported fill	$ 3.90
6 inch lime stabilized subgrade	$ 2.45
Total approximate cost, I-635 East of I-35E	$ 26.35
Cost differential, Section 1 to 2	$ 15.40

Figure 1. Observed westbound pavement warp, I-635 near MacArthur Boulevard, Irving, Texas. Design section shown in Figure 4.

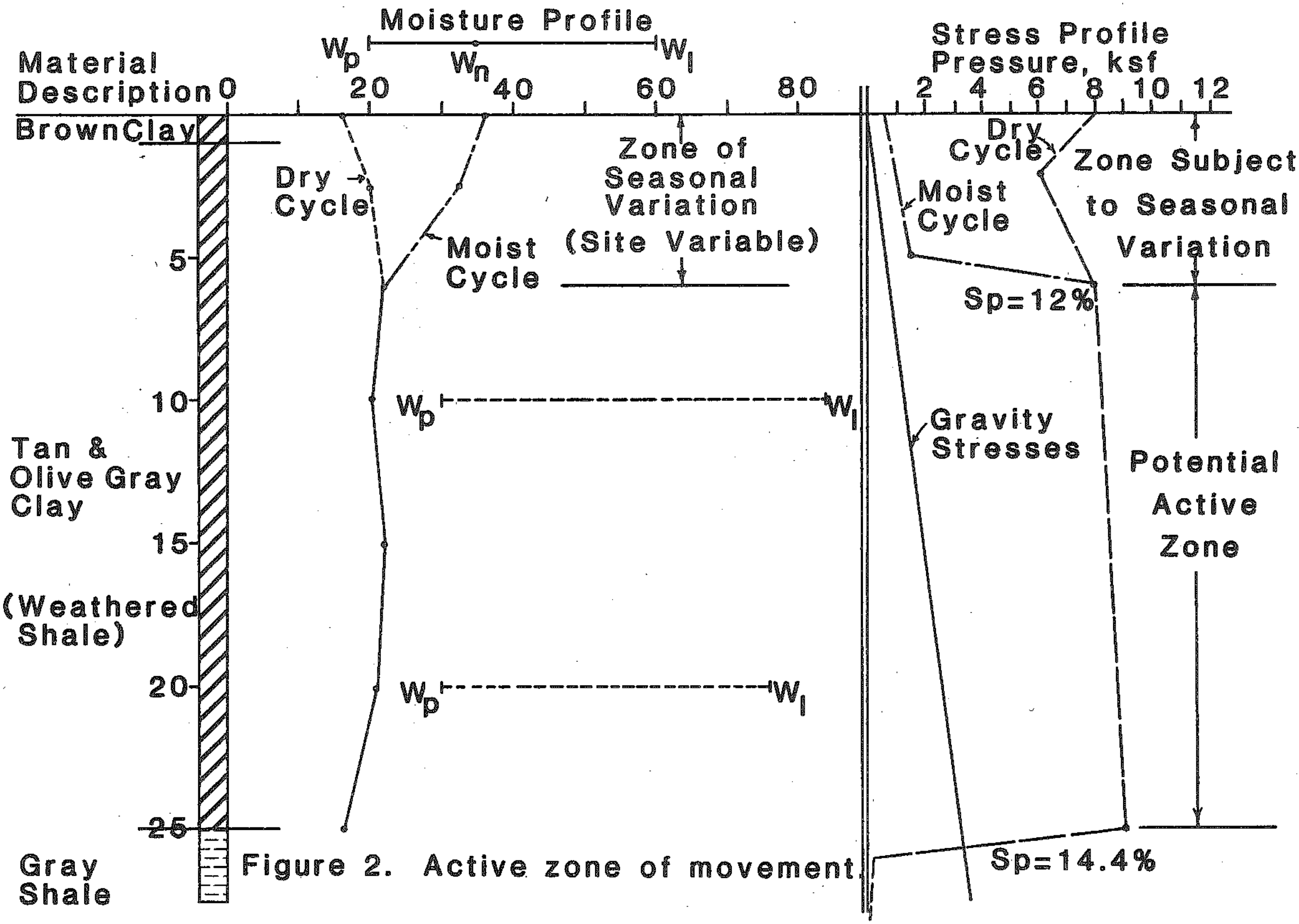
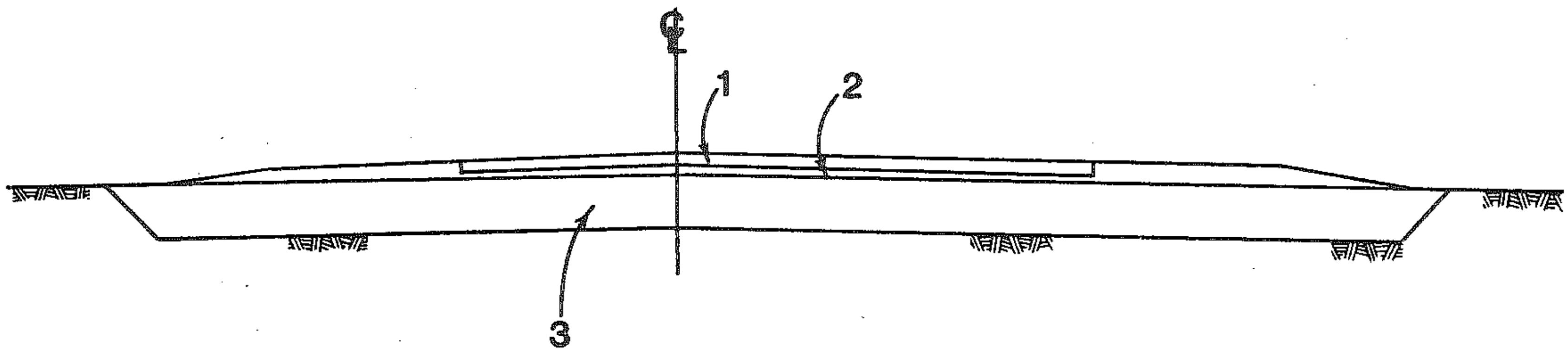


Figure 2. Active zone of movement.



1. 9" Concrete paving
2. 4" Asphalt stabilized base.
3. 36" Select fill with PI between 4 & 20.

Figure 4. Design section, site 2, westbound I-635 at MacArthur Blvd.

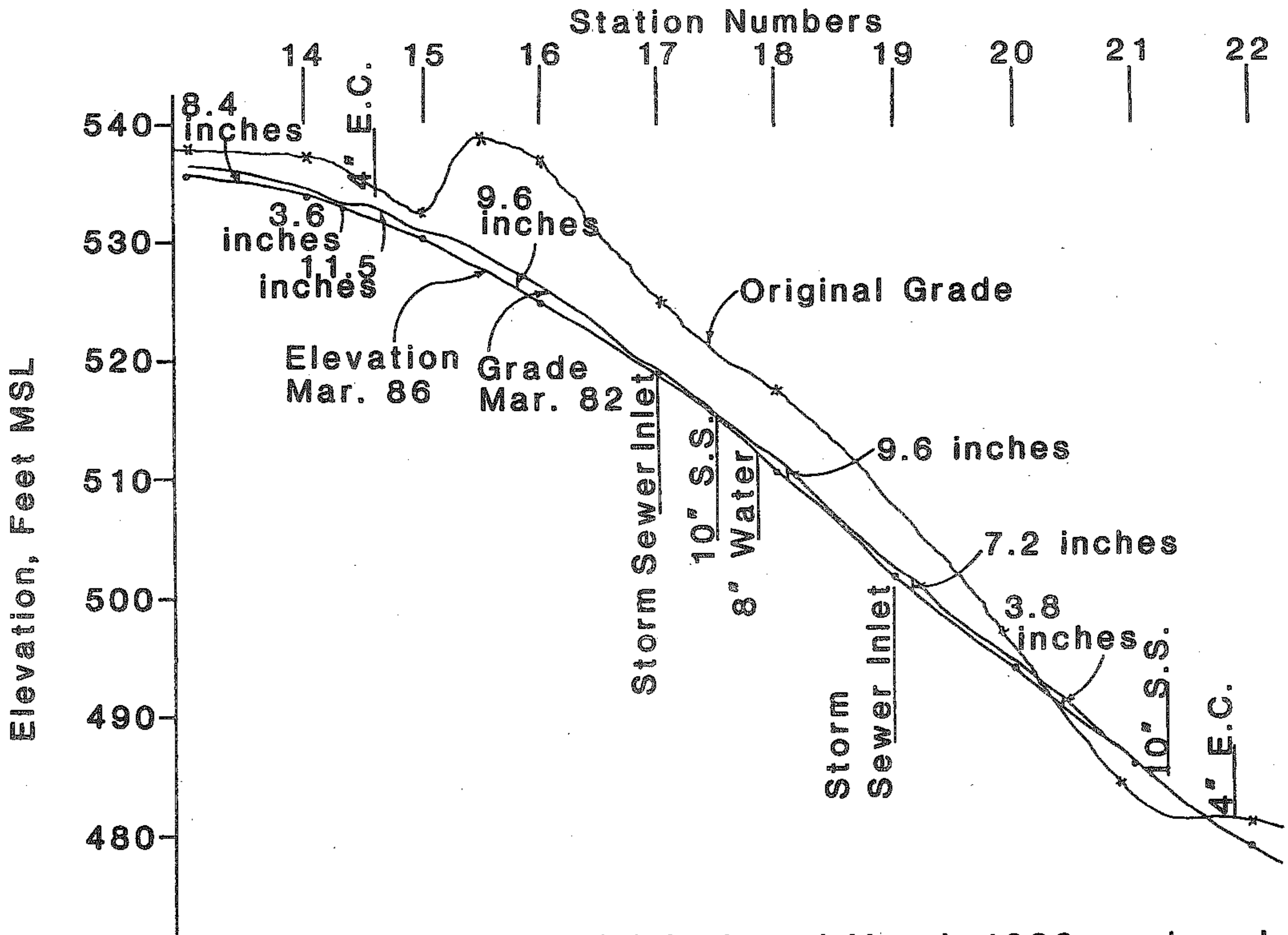
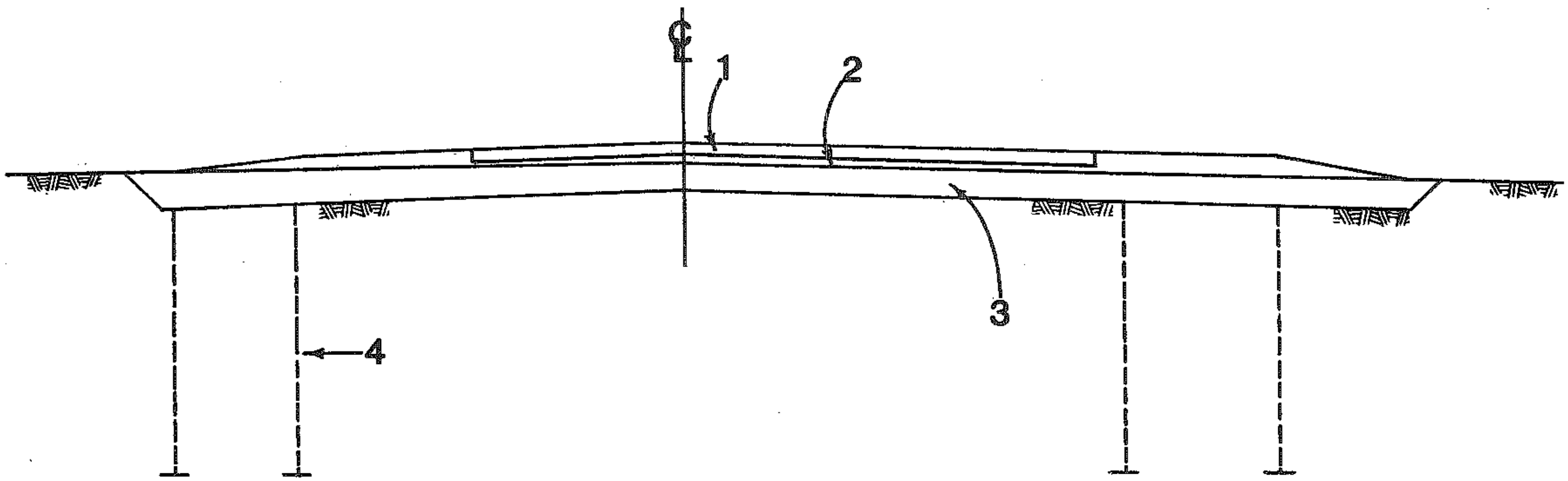


Figure 6. Natural, finished, and March 1986 grades along the east curb line, site 3, MacArthur Blvd.



1. 9" Concrete paving.
2. 4" Asphalt stabilized base.
3. 20" Lime stabilized fill & subgrade.
4. 1 Lime – 3 Water injections to 8′ depth.

Figure 7. Alternate highway design with preswelled subgrade.