Failure and Repair of the Slope of Railway Embankments and Expansive Soils

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SYNOPSIS: This paper mainly discusses the stability of the slope of the four sections of railway embankments of expansive soils, describes their basic condition and the properties of the soil materials, analyzes the types and causes of slope failures, discusses the repair of such slopes, and the remedial measures to prevent recurrent of the slides, and sums up experience of using expansive soils to construct railway embankments.

PREFACE

In China, there are extensive deposits of expansive clays. It is almost impossible to avoid using them to construct railway embankents. It is estimated that at present there are many hundreds of kilometers of railway embankments constructed of this soil, which is particularly susceptible to sliding. Railway traffic is endangered or delayed, and sometimes there are accidents caused by the slides.

The repair of such slopes, and the remedial measures to prevent recurrence of the slides is the topic of this paper. Four case histories illustrate the problem and solutions.

THE XIANG-YU RAILWAY K317+280 - K317+366

An 86 meter long, 24m high section of a long embankment was constructed with a local expansive clay fill. Its properties were:

$LL = 45.3\%$, $PL = 17.4\%$, $PI = 27.9$, $SL = 10.2\%$

<5μ soil particle content $X_5 = 47.5\%$,

<2μ soil particle content $X_2 = 38.0\%$,

free swell of disturbed sample $FS = 65.0\%$,

percent of volume change from saturation to air-dry $\delta_m = 26.2\%$, swelling pressure $p_s = 150KPa$.

The shear strength parameters of the compacted soil ($w = w_{op}$, $\gamma_d = \gamma_{dmax}$):

undrained shear test: $c = 50KPa$, $\Phi = 12°$;

saturated undrained shear test: $c=25KPa$, $\Phi = 8°$.

There are three sets of tracks on the embankment, which was completed in 1973. The upper approximately ten meters of the embankment at 1v:1.5h are steeper than the lower portion at 1v:1.75h. Transverse 2.5m wide stone-filled drains have been placed in the slope, spaced at approximately 8 meters. The drains are approximately 1.5 to 2.0m deep. Between them are arch-shaped drains. A retaining wall was constructed at the foot of the slope.

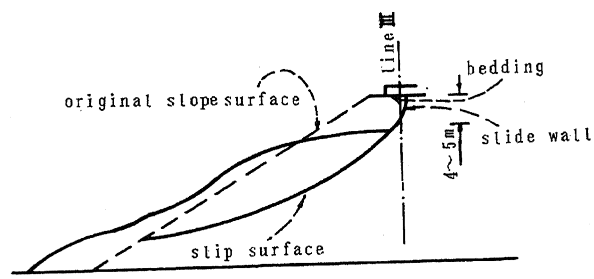


Figure 1

The rainy season in the region of the embankment is from July to September. On the 11th of October, 1980 a slide occurred on the slope of the embankement. See Fig. 2. The slide was about 50m wide, and about 4 to 5m thick. The slide scarp was about 0.3m on the 12th, 2.0m on the 19th, and was about 4 to 5m high by the 21st of October. The drains on the slope and the retaining wall at the foot of the slope were damaged, and the rails were suspended from their ends, due to the removal of support by the embankment.

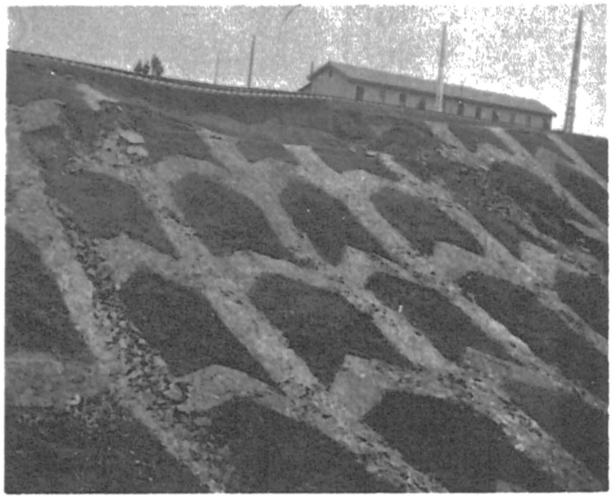


Figure 2

Reasons for the failure:

1. It is unstable to construct such a high embankment with the expansive soil with a slope of 1:1.5 to 1:1.75. A stability analysis based on the saturated undrained shear strength shows that the factor of safety is less than 1.

2. Since there was poor drainage on the surface of the embankment, water accumulated under the ballast bedding. Such accumulation seeped into the embankment, softening the soil.

3. Water accumulation under the ballast bedding softened the embankment and allowed penetration of ballast into the bedding, causing a ballast pocket. See Fig. 3. In turn, this pocket became a reservoir for further accumulation of water and fed the water into the embankment.

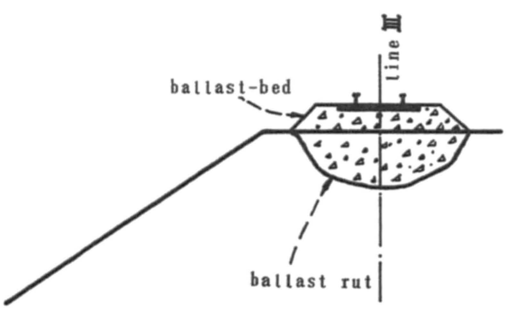


Figure 3

4. The original density of the embankment was low and not uniform, since compaction had been attempted with earth-hauling machinery, and probably without proper rolling. Moreover the slope surface was not well protected so that shrinkage cracks formed in the dry season, with rain infiltrating these cracks during the rainy season.

5. The rock drains on the slopes were apparantly too shallow.

The main repair measures that were adopted are shown in Fig. 4.

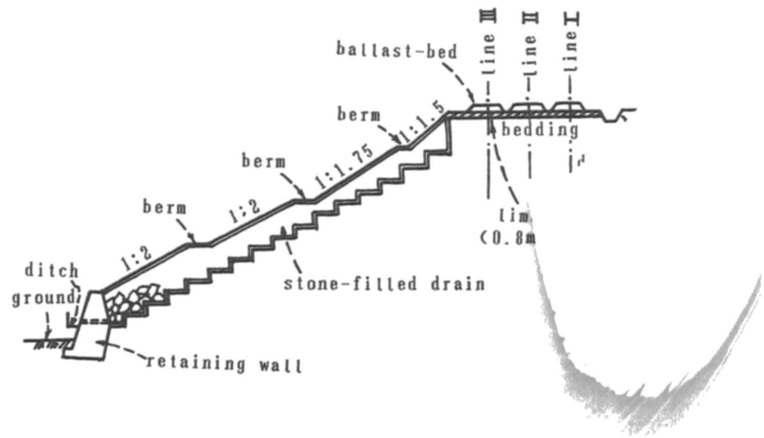


Figure 4

1. A lime-soil mixture with a ratio of lime to sand to soil of 1:5:10 was used as a 0.8 meter thick bedding just below the ballast. A longitudinal ditch was set on the embankment to drain surface water.

2. After removing the slide materials, local expansive soil was mixed with 25% sand and recompacted, with overall slope steepness reduced and three small berms introduced.

3. Nine transverse rock drains, 2m wide, and spaced 8m apart were built to extend one-half meter below the slip surface. Between the transverse drains, rock arch-drains were constructed. See Fig. 5.

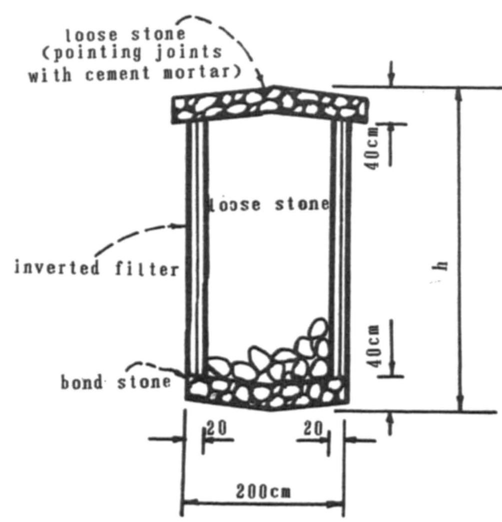
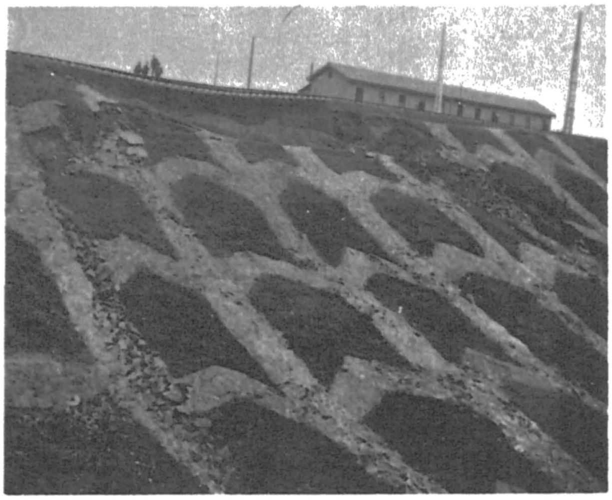


Figure 5



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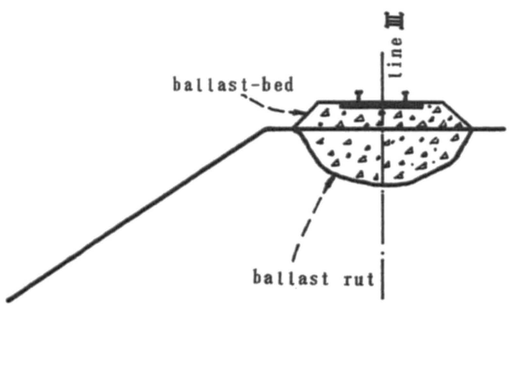

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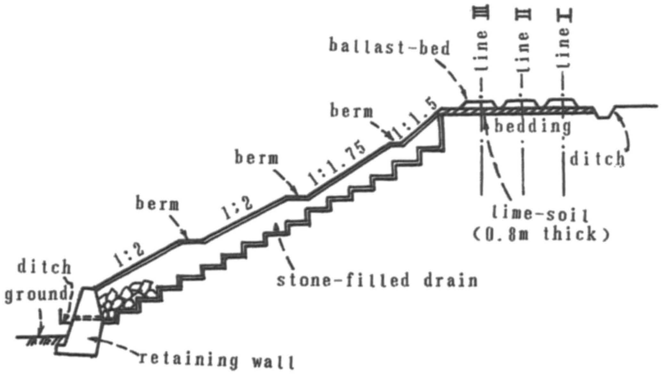

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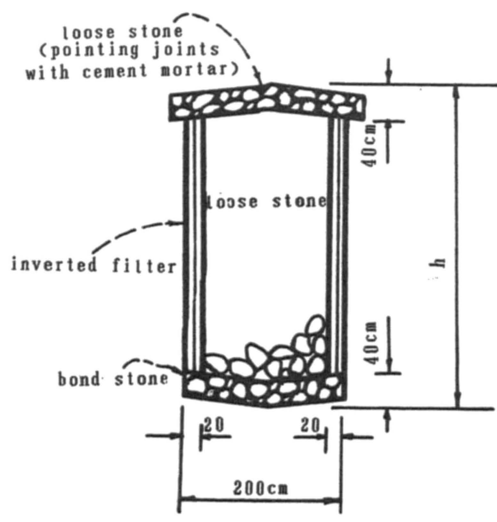

Figure 5

4. A seven to eight meter high retaining wall with a base width of 3.8m was built at the foot of the slope.

The embankment was repaired in November 1983. Since that time the slope has been stable and the embankment has been completely serviceable.

THE XIANG-YU RAILWAY K310+325 TO 310+480

This embankment is 155m long, with a maximum height of 26.7m. The upper six meters of the embankment has a slope of 1v:1.5h; from 6 to 18m below the crest the slope is 1v:1.75h; and where the embankment is higher than 18 meters, all below that height is 1v:2h. There was no slope protection built into the embankment in 1973, when it was constructed of local expansive clays. The properties of this clay were:

LL = 43.6%, PL = 18.5, PI = 25.1,
SL = 11.0%,
X_5 = 48.3%, X_2 = 35.3%,
FS = 68.0%, δ_m = 27.4%, p_s = 120KPa.

The shear strength parameters of the compacted soil ($W = W_{op}, \gamma_d = \gamma_{dmax}$):

undrained shear test: c = 55.0KPa, $\Phi = 10.5^\circ$, saturation undrained shear test: c = 36.0KPa, $\Phi = 7.6^\circ$.

The failure consisted of multiple shallow slides in the middle sections of the slope during the rainy season of 1974. These slides covered more than half the area of the slope between the above referenced stations. The slides initially took the shape of a horse's hoof, and were relatively small in area. See Fig. 6. The individual slides were about 10-20m wide, and 0.8-2.0m thick. As they developed, several of the slides joined and overrode one another, and then continued to expand up the slope. It was anticipated that if not repaired promptly, sliding would result in the rails losing support.

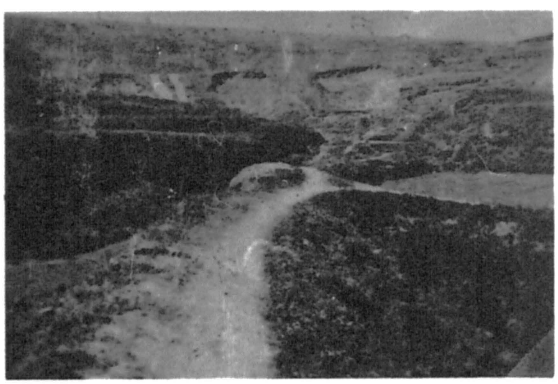

Figure 6

It was evident that this failure resulted from a shallow layer of the slope becoming saturated due to water seepage, rapidly reducing the shear strength of the soil. Specifically:

1. The rainy season of 1974 was long and rainfall was heavy.
2. Compaction of the embankment had been done using hauling equipment rather than with rollers, and the compaction was poor and non-uniform.
3. Shrinkage cracks had appeared before the rainy season, and had not been repaired at the time of the rains.
4. The slope was too steep. Soil tests on a sample which had been permitted to swell in water gave shear parameters of C = 10 KPa and Φ = 4 degrees. A stability analysis was made with the assumption that the slip surface was a plane, and the factor of safety of the slope was determined to be less than one.

Measures to repair the slope were as follows:

1. Fifteen transverse stone drains were constructed on the slope at 10m spacing. The drains were 1.5m wide and 2m deep. Between the transverse drains arch-drains were constructed as shown in Fig. 7.

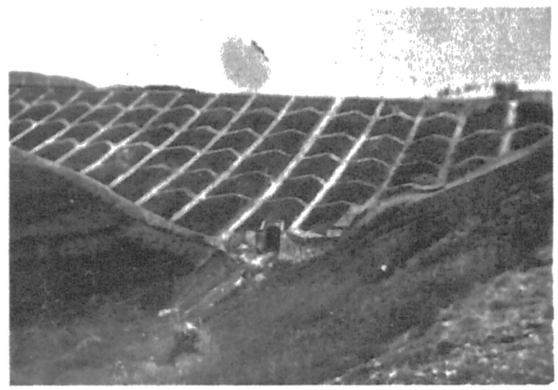

Fig. 7

2. Between the drains were planted a bush called False Indigos which has roots that can reach 2-3m deep. These bushes were expected to reinforce the slope.
3. A longitudinal ditch was built at the foot of the slope.

Repairs were completed in 1977. In the intervening ten years the slopes have remained in good condition and there has been no evidence of sliding or distress.

THE JIAO-ZHI RAILWAY K703+700 TO K704+300

The embankment is 600m long with a height of 8-14m. The upper 10m of the slope are at 1v:1.5h, and below this 1v:1.75h. The fill is local expansive soil without slope protection. Two soils were used, a gray clay and a brown clay. Their properties are given in tables 1 and 2.

The embankment was completed in 1970. The slopes began to fail during the rainy season during the first year that it was open to traffic.

The failures appeared chiefly in the form of shallow slides. Generally these slides were limited to the top two-thirds of the embankment with a width of 10-30m and usually about 1 to 1.5m in thickness. Slide scarps were generally 1.0-1.5m in height. Fig. 8 shows details.

There were very many slides along the slopes of the embankment.

Table 1. Basic Properties of the Soil Materials

soil type	LL	PL	PI	X_5	X_2	FS	SL	δ_m	p_s
	%	%	—	%	%	%	%	%	KPa
gray clay	50.7	18.3	32.4	49.5	39.0	85.0	11.2	44.5	150
brown clay	46.5	19.4	27.1	40.2	28.5	65.0	10.7	27.9	90

note: X_5 —— <5μ soil particle content;

X_2 —— <2μ soil particle content;

δ_m —— percent of volume change from saturation to air-dry;

p_s —— swelling pressure.

Table 2. Shear Strength Properties of the Compacted Soil

soil type	undrained shear		saturation undrain shear	
	C (KPa)	φ (°)	C (KPa)	φ (°)
gray clay	60.5	8.0	31.5	5.0
brown clay	90.0	10.2	40.0	6.0

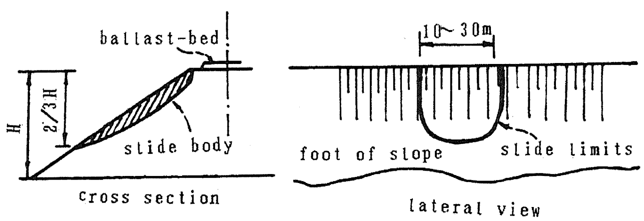

Fig. 8

It was obvious that the failures of the slopes were the results of poor compaction of the slopes, lack of protection for the slope surface, and surface water seeping into the slope through shrinkage cracks or hollows in the slope and shoulder of the crest. In some cases water had accumulated in ballast pockets, and was aggravating the problem.

As shown in Fig. 9, at some places the surface water caused successive shallow slides which eventually undermined the track at the top of the embankment.

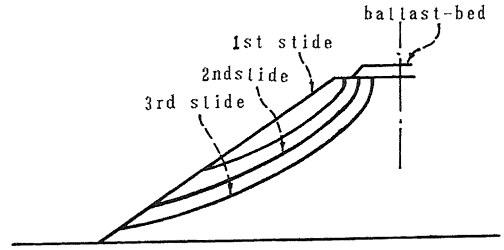

Fig. 9

In addition, slides occurred with slide scarps 2-3m high beneath the tracks, with slide bodies 30-40m in width and 2-3m thick. These formed because the saturated ballast pockets 1-1.5m deep were squeezed outwards under the loading of the trains. Both surface water and water that had accumulated in the ballast pockets served to saturate the embankment.

For this embankment the repair was effected by placing sand on the surface of the embankment to a depth of 1.5-2m, as shown in Fig. 10.

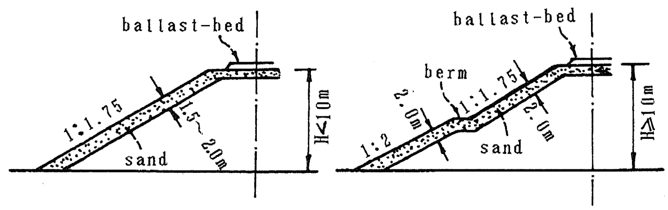

Fig. 10

1. The sand layer was designed to be 1.5m in thickness where the embankment was less than 10m high, and 2m in thickness for a higher embankment section. Under the ballast, sand was 1m thick.

2. Where there were deep ballast ruts or pockets, transverse stone-drains were constructed.

3. The slope gradient was changed so that the upper 10m of the embankment had 1v:1.75 slopes, and below this 1v:2h. A berm of 1.5-2m in width was constructed where the slope gradient changed 10m below the top of the embankment.

4. Naturally occurring grass was planted for protection on the slope.

It has been well over ten years since the embankment was repaired in 1975. The embankment has been completely serviceable during this time. The sand of the shoulder at the crest and along the slope surface has slipped somewhat, but not sufficiently to warrant concern or repair.

THE XIANG-YU RAILWAY K309+636 TO k309+701

This 65m long section of 30m maximum height is part of a long embankment across a valley. As with the other cases cited, the upper slope was 1v:1.5h with a 2.5m wide berm and a lower slope of 1v:1.75h. On the berm a ditch was built. There was no other slope protection. The embankment material was again an expansive clay with the following properties:

$LL = 43.6\%$, $PL = 18.5\%$, $PI = 25.1\%$,
$SL = 11.0\%$,
$X_5 = 57.0\%$, $X_2 = 32.5\%$,
$FS = 57.0\%$, $\delta_m = 26.5\%$, $p_s = 100$ KPa.

The shear strength parameters of the compacted soil ($W = W_{op}$, $\gamma_d = \gamma_{dmax}$):
undrained shear test: $c = 63.5$KPa, $\Phi = 14.1^\circ$
saturation undrained shear test:
$c = 28.0$KPa, $= 7.5^\circ$.

Three railway lines were placed on the embankment. The project was completed in 1973.

Three shallow layer slides occurred on the slopes in the rainy season of 1981. A large amount of surface water had seeped into the slope. Makeshift measures were taken to effect a quick repair; timber piles were driven through the slide and straw bags packed with soil were placed to be a counterweight for the side. Each of the three shallow layer slides began to migrate upwards, so that the slide body became about 30m wide, 1.5-2m thick with slide scarps about 1.5m high. Fig. 11 depicts this.

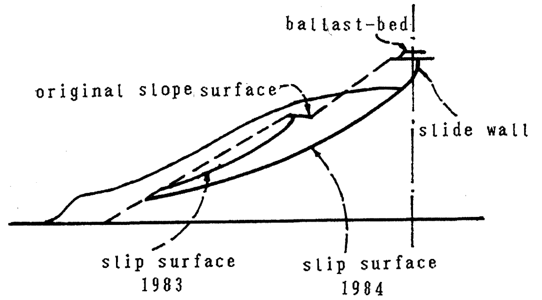

Figure 11

In September 1984, as the slide was being repaired, it rained almost continually for 20 days. A large slide about 60m wide, 4-5m thick with a slide scarp 3m high occurred from the top of the embankment, resulting in loss of support and suspension of 20m of rail.

The causes of the slide appeared to be:

1. The design slope was too steep. Using the saturated undrained shear strength of the embankment soil, a stability analysis showed that the factor of safety was less than 1.
2. Neither drainage ditches on the embankment surfaces nor slope protection was provided. Large ballast pockets had formed under the track and surface water had seeped into the slope from the pockets.

Fig. 12 shows the remedial measures taken to repair the slope.

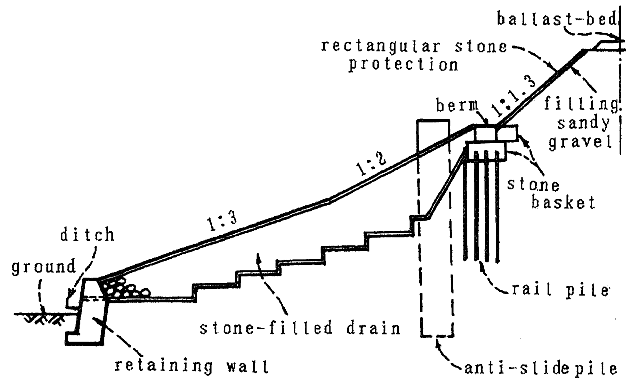

Fig. 12

1. The slope gradient was reduced. The upper 9m was 1v:1.3h, from 9 to 18m below the crest of the embankment, the slopes were 1v:2h, and all embankment below 18m was made with a 1v:3h slope. At the nine meter level a berm 2m wide was constructed. Two hundred twelve rail piles 12.5m long, at 1m spacing were driven below the berm. Reinforced stone baskets were placed on them. Just below the piles and stone basket on the slope were placed four large reinforced concrete anti-slide piles of 3.7m by 2.5m section 25m long.
2. After removal of the slide material, on the top 1:1.3 portion of the slope sandy gravel was placed on the surface with loose rectangular stone as surface protection.
3. From the level of the berm down, nine transverse stone-filled drains were built at 8m spacing, 3m wide, extending below the sliding surface. Between the drains the slope surface was placed a 1m thick layer of soil mixed with 30% sand and rammed in place. False Indigo was also planted on the slope.
4. A retaining wall 5m high with a 3m wide base was built at the base of the slope.

The repairs were made in the first half of 1986. Since then it has been subjected to two rainy seasons. Performance has been excellent.

CONCLUSIONS

1. There are two basic types of slope failures in embankments constructed of expansive clay, normal slides and shallow layer slides. The former is large in scale and quite severe. Shallow layer slides, the more common, must be promptly repaired or they, too, will become severe.

2. In expansive soils shear strength rapidly decreases after the soil swells upon saturation with water. The effects of this shear strength decrease have not been considered in design and construction in the past. The immediate causes of failure are too steep a slope, improper slope protection, poor drainage, formation of ballast pockets and their saturation, rutting of the ballast, poor compaction and improper maintenance.

3. Provided that proper measures are taken in the design and construction, it is possible to ensure the slope stability of an expansive soil embankment. It is not impossible to construct a proper embankment of expansive soil. Restraining the use of expansive soils in embankments results in higher costs.

4. The most important consideration in the design of such an embankment on expansive soil is to use the proper saturated shear strength of the soil, to perfect the slope protection and drainage system, to treat the bedding for the ballast to prevent rutting and ballast pockets, and to ensure proper compaction during the construction.

ACKNOWLEDGMENT

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SYMBOLS AND NOTATIONS LIST

FS Free Swell
LL Liquid Limit
PL Plastic Limit
PI Plasticity Index
SL Shrinkage Limit
C Cohesion (KPa)
γ_d Dry Unit Weight (KN/m^3)
γ_{dmax} Maximum Dry Unit Weight (KN/m^3)
P_s Swelling Pressure (KPa)
W Water Content
W_{op} Optimum Water Content
X_2 2 Soil Particle Content
X_5 5 Soil Particle Content
δ_m Percent of Volume Change from Saturation to Air-Dry
Φ Angle of Internal Friction