SRI LANKAN GEOTECHNICAL SOCIETY

ANNUAL CONFERENCE

"GEOTECHNICS IN ROAD SECTOR"

27th September 2012

At the Wimalasurendra Auditorium

Institution of Engineers- Sri Lanka

Stabilization of Highway Cut Slopes In Sri Lanka

Prof. Athula Kulathilaka
University of Moratuwa

Most Slopes in Sri Lanka are formed by Residual Soils and Colluvial Soils

Residual Soils
Produced by the in situ weathering of the parent rock. Remain at the location of the parent rock

Colluvial Soil
Weathered product has moved down under gravity -(seen at the sites of old landslides)

- Sri Lankan Land mass Consists mainly of Metamorphic and Igneous Crystalline rocks
- Principal rock types are Gneisses, Charnockites, marble and Quartzite.
- Metamorphic Rocks retain their original bedding planes which are now referred to as foliation planes. These rocks could have banded structures with one or more joint planes
- These planes of discontinuities will remain as relict joints in the weathered product (Residual soil)

Tropical Weathering Conditions of;

- High ambient temperature
- High rainfall and humidity

together with

- Mineralogical changes in the parent rock

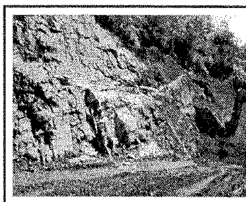
Leads To ;

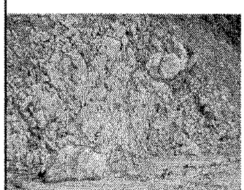
Highly heterogeneous - irregular soil/rock profiles

With considerable variation over short distances

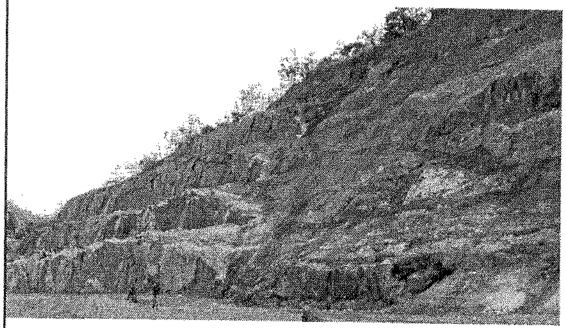
- Part of the slope formed of Charonockitic rock may remain unweathered while the surrounding rocks have completely weathered
- Some rocks such as Feldspar rich gneisses, migmatitic biotite gneisses have lead to the formation of clay rich soils which are highly vulnerable to erosion and are of lower shear strength.

Degree of Weathering and the Nature of the weathered product varies within a short distance





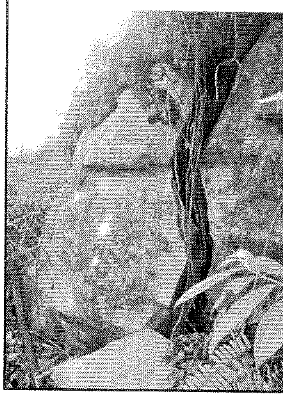

1



Charconckitic Rocks that have high resistance to weathering Remains un-weathered - known as Boudings

Charconckitic Boudings in a Matrix of Completely Weathered material

Rocks with closely spaced Joints
Those will remain as "Relict Joints" after weathering



A rock Joint Widened by a tree grown within

- At the right flank of the landslide at 36+

Slope Instability Triggered by Rainfall

- Residual soils forming these slopes are mostly unsaturated during the dry season and they may possess quite high matric suctions.
- With the infiltration of water due to rainfall, matric suction will be reduced or completely lost. Positive pore water pressures may also develop
- The shear strength τ_f will decrease and the Factor of safety will reduce. When it approaches unity slope failures will occur
- Hence the understanding of this process of infiltration and loss of matric suction is very important

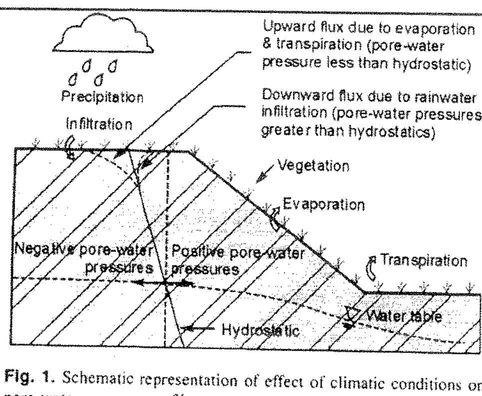
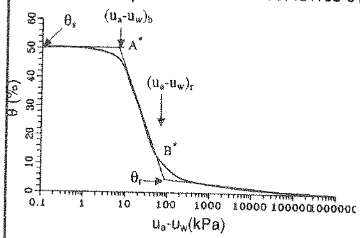
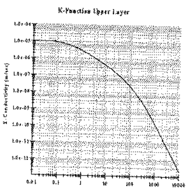


Fig. 1. Schematic representation of effect of climatic conditions on pore-water pressure profile near ground surface of slope

Two Most Important Characteristics of an Unsaturated Soil

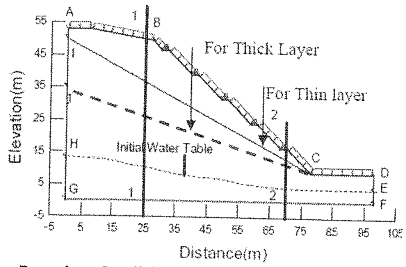


Idealized Soil-Water Characteristic Curve

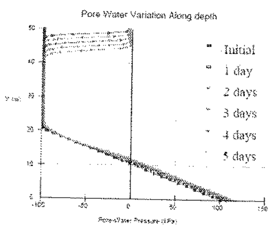


Hydraulic conductivity (Permeability) function

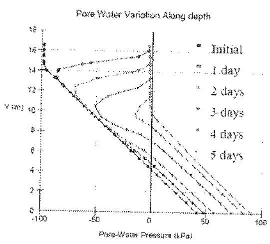
Modelling the Transient Seepage Analysis with SEEPW Software
For three different conditions in sub soil
Case 1, Case 2 and Case 3



Boundary Conditions
AB, BC, CD= Ir (Rainfall intensity)
AH, DE, FG=Q=0m³/s (No flow Boundary)
EF, GH=ht (Total head at sides)



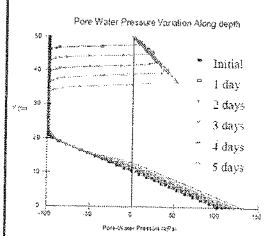
(a) For Section 1-1



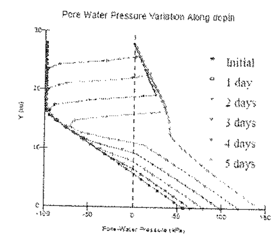
(b) For Section 2-2

Section 1-1 Section 2-2

Results of 5mm/hr Rainfall for Case1



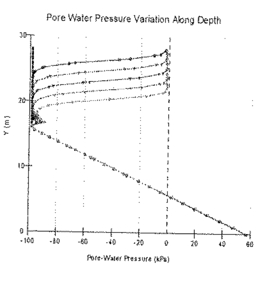
(a) For Section 1-1

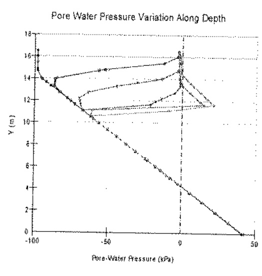


(b) For Section 2-2

Section 1-1 Section 2-2

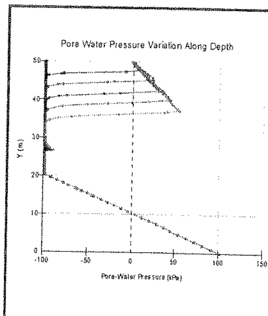
Results of 20mm/hr Rainfall for Case1

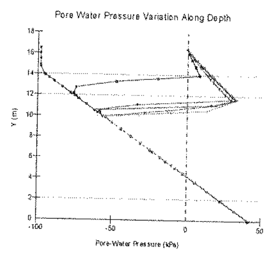




Section 1-1 Section 2-2

Results of 5mm/hr Rainfall for Case 2





Section 1-1 Section 2-2

Results of 20mm/hr Rainfall for Case2

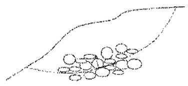
3

Factor of safety of a slope is defined as;

$FOS = \tau_f / \tau_m$

Where τ_f - shear strength

τ_m - shear stress mobilized for equilibrium



Shear strength of a Saturated Soil

$\tau_f = c' + (\sigma - u) \tan \phi'$

Where, c' - effective cohesion

ϕ' - angle of internal friction

σ - total stress

u - pore water pressure

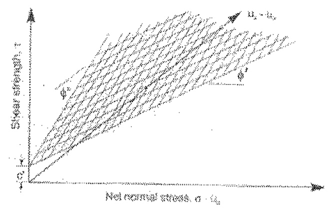
Shear Strength of unsaturated soils given by,

$\tau_f = c' + (u_a - u_w) \tan \phi^b + (\sigma - u_a) \tan \phi'$

Where

$u_a - u_w$ - matric suction - negative pore water pressure

c_a - apparent cohesion = $c' + (u_a - u_w) \tan \phi^b$



·As seen with the analysis presented, With the infiltration of water due to rainfall, matric suction will be reduced or completely lost. Positive pore water pressures may also develop

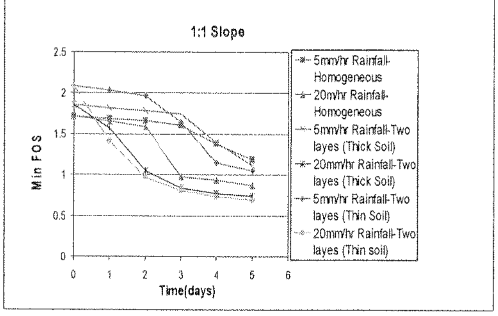
·Presence of layers of different degrees of weathering (permeability) will affect the changes in the pore water pressure regime.

·The shear strength τ_f will decrease and the Factor of safety will reduce. When it approaches unity slope failures will occur

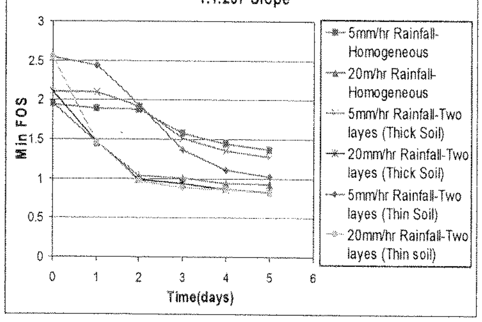
---

Parameters Used for the Stability Analysis with SLOPE W Software

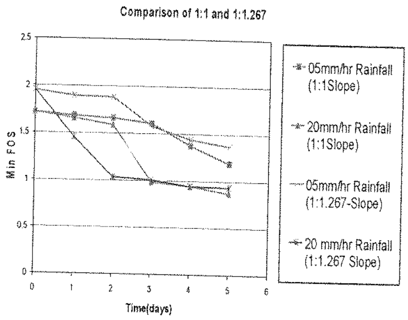
	Unit Weight (γ_{eff})	Friction angle (ϕ')	(ϕ^b)	(c')
Residual Soil				
Mean	19	34	30	10
S Deviation	0.5	1.5	2	1.5
HWR				
Mean	20	40	38	25
S Deviation	0.5	1.5	2	1.5



Variation of factor of safety with duration of rainfall



Variation of factor of safety with duration of rainfall -1:1.267 slope



Comparison factor of safety - slopes of 1:1 and 1:1.267 with uniform soil

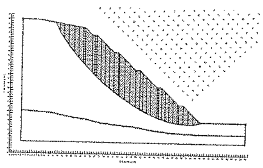
The results of the analysis illustrates that making the Slope flatter may not necessarily ensure the stability during long duration rainfalls.

Hence, Our attempt should be to;

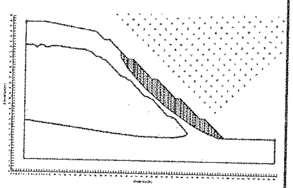
Reduce infiltration, minimise the loss of matric suction and reduce the pore water pressure built up

This can be achieved by

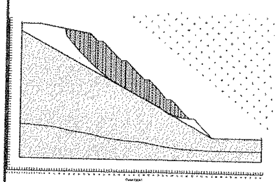
- Improving Surface drainage
- Providing sub surface drainage



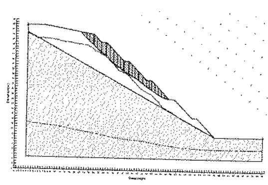
Shape of typical critical failure surface - homogeneous soil slope at initial stage



Shape of typical critical failure surface - homogeneous slope at a later stage



Shape of typical failure surface - two layers of soil slope at initial stage



Shape of typical critical failure surface -two layers of soil at a later stage

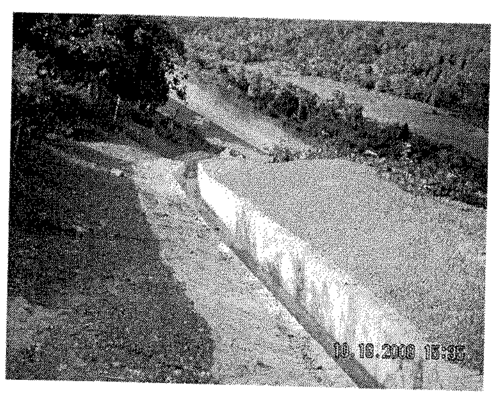
Surface drainage should be enhanced by the construction of Cut off drains, berm drains berm seals.

Appropriate Vegetation or artificial Slope Cover such as shotcrete or Chunam plaster could minimize infiltration and prevent erosion as well.

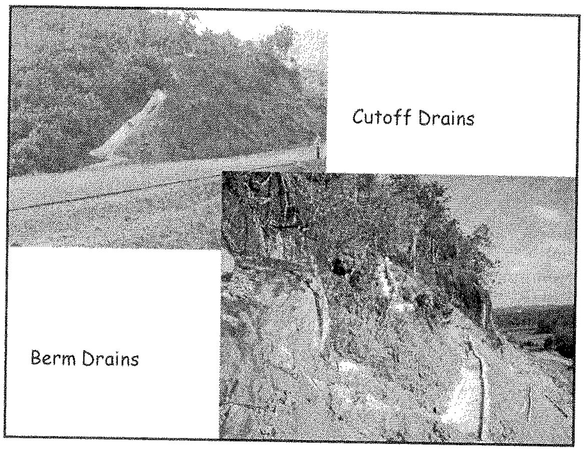
Special attention should be given to highly erodible soils

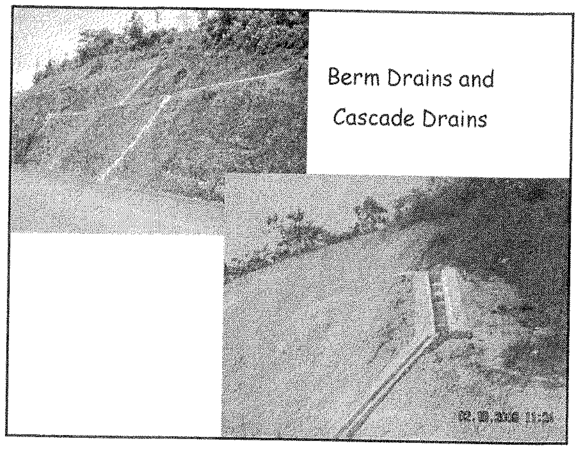
Infiltration into relict joints should be prevented by sealing.

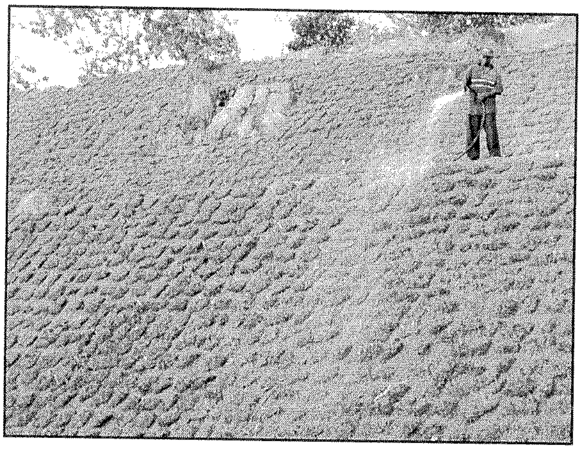
Sub surface drains may be required in some situations.

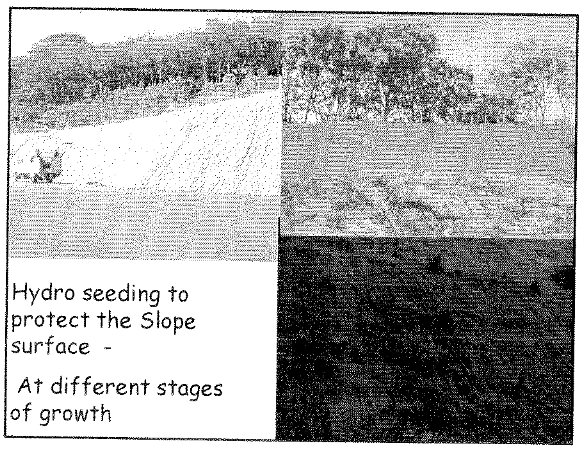


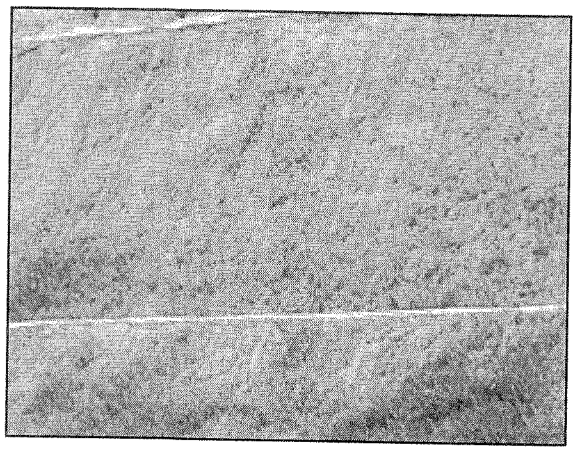
5


Cutoff Drains
Berm Drains

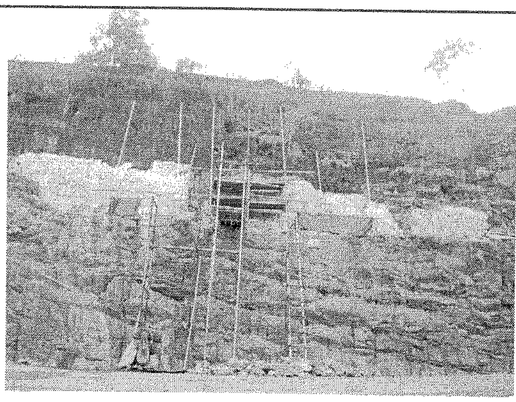

Berm Drains and
Cascade Drains



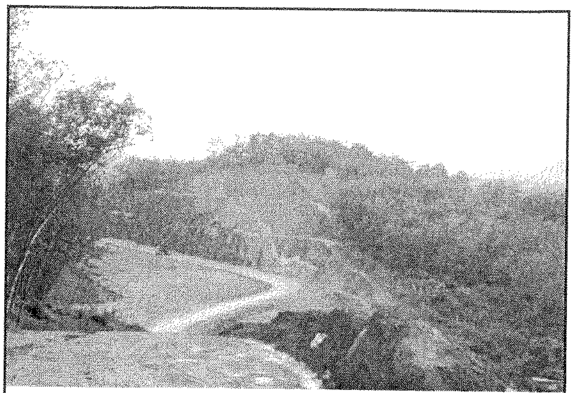

Hydro seeding to
protect the Slope
surface -
At different stages
of growth



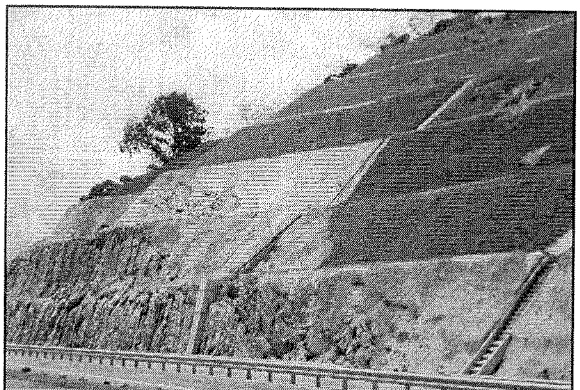
6



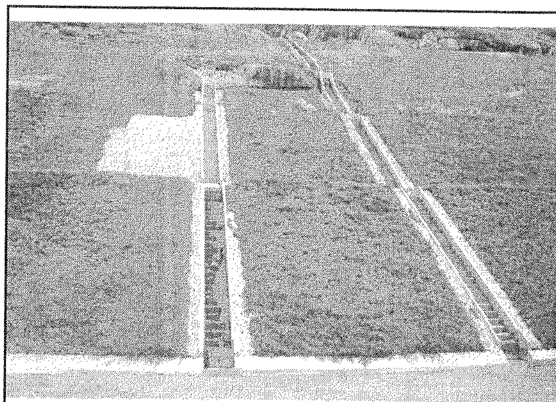
Cavity Filling

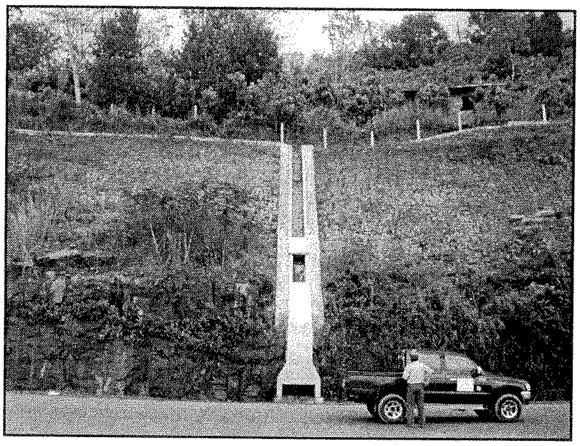


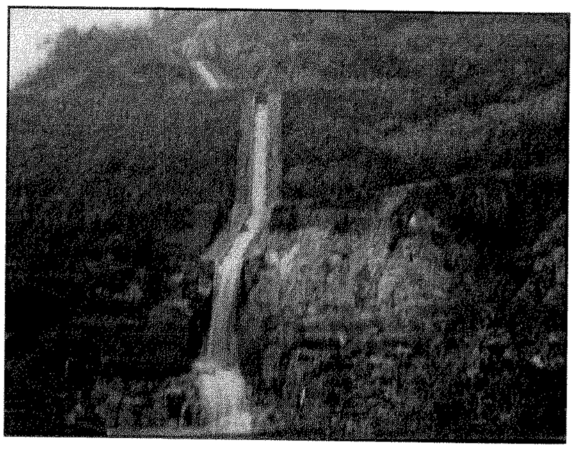
Repair of Erosional gullies



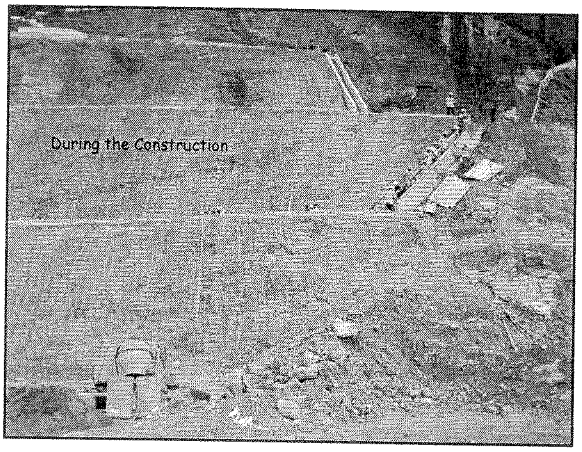
A single cut slope may demand different erosion protection measures

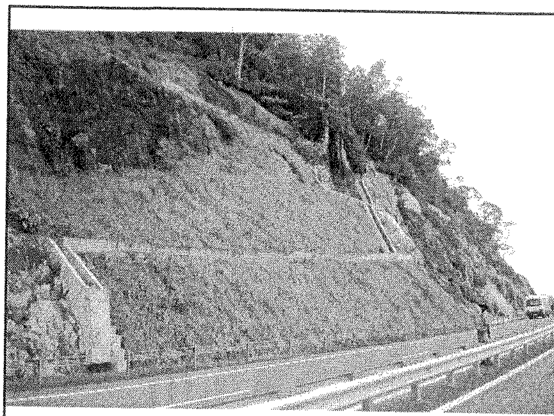






7



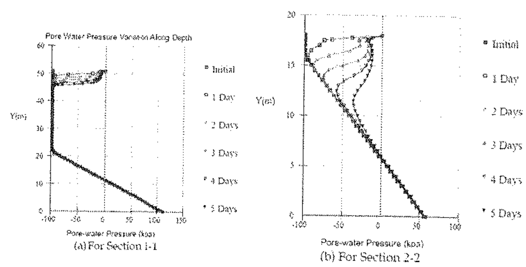


Study of Effectiveness of Surface Drainage Measures

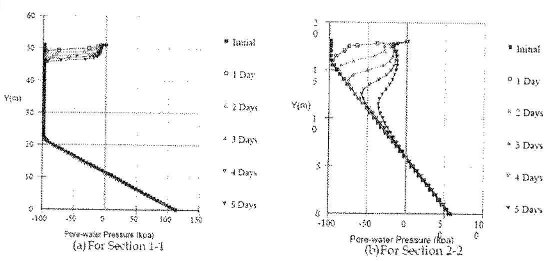
With the use of sealed drains in the berms, cascade drains to allow rapid passage of water down the slope and appropriate vegetation cover over the slope surface, the infiltration of rainwater can be reduced.

The effectiveness of the said surface drainage measures were studied using the SEEPW program. The influence of the vegetation cover was modeled by incorporating a 100mm thick layer of permeability in the range 10^{-6}m/s to 10^{-9}m/s.

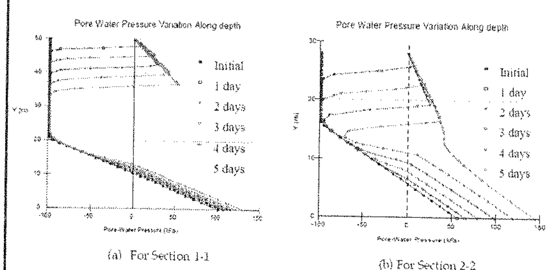
The stability of the slopes after a rainfall event was analyzed using the SLOPEW program.



pore water pressure distribution for 5mm/hr rainfall with vegetation layer of permeability 10^{-7}m/s (Case 1)



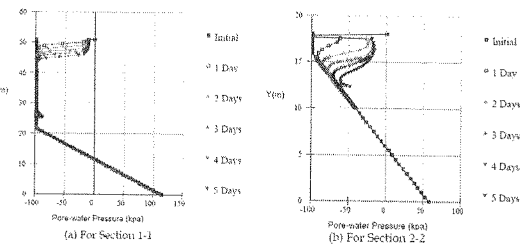
Pore water pressure distribution for 20mm/hr rainfall with vegetation layer of permeability 10^{-7}m/s (Case 1)



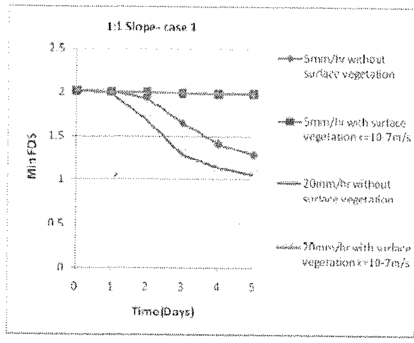
Section 1-1 Section 2-2

Results of 20mm/hr Rainfall for Case1 when there is no vegetation cover

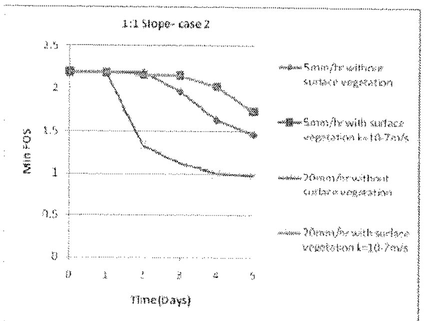
8



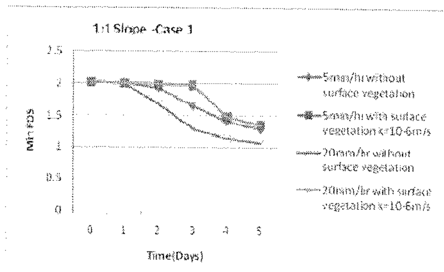
Results of 20mm/hr Rainfall with vegetation layer of permeability 10^{-7}m/s for Case2



Variation of factor of safety with duration of rainfall - 1:1 slope- Case 1



Variation of factor of safety with duration of rainfall - 1:1 slope- Case 2



Factor of safety with duration of rainfall - Vegetation of permeability 10^{-6}m/s- 1:1 slope- Case 1

The results showed that the use of a 100 mm thick vegetation cover of permeability 10^{-7}m/s, which is practically achievable, could cause a significant reduction in infiltration and the prevent formation of a perched water table and minimize the destruction of the matric suction.

The study was done for different geological condition of a uniform residual soil and a residual soil underlain by weathered rock,(Case1, Case 2 and Case3) and all three geological conditions showed a similar response.

The study also revealed that a vegetation cover with a permeability of the order of 10^{-6} m/s would be less effective in maintaining a sufficient safety factor during a prolong rainfall. As such, Studies should be conducted to identify appropriate type of vegetation.

To maintain a sufficient safety margin, some Slopes may require sub surface drainage in addition to the above surface drainage measures

Sub surface drainage facilitate the movement of water already gone into the soil and accelerates the pore water pressure dissipation.

In some situations

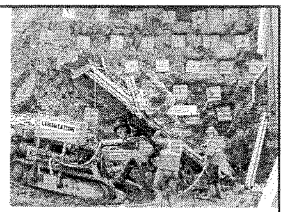
Further external support through Earth Retaining Structure or

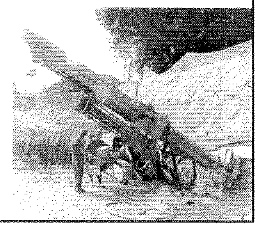
Internal Stabilizing Systems such as Soil nailing may also be required

Vegetation will also be helpful by enhancing the shear strength of the soil through its system of roots.

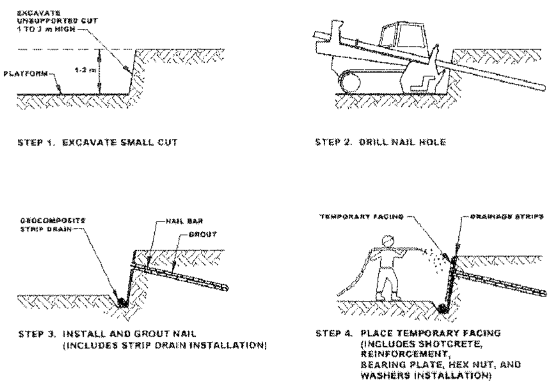
Soil Nailing Technique

- Nails
  - Driven Nails
  - Drilled and Grouted Nails
  - Corrosion Protection Systems
  - Proprietary Systems
- Facing
  - Wire Mesh Facing
  - Shotcrete Facing
  - Hydro seeded Facings



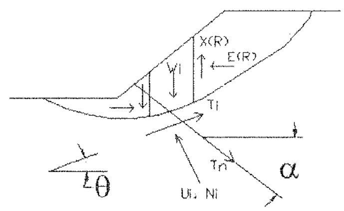


Construction Sequence of a Soil Nail Wall

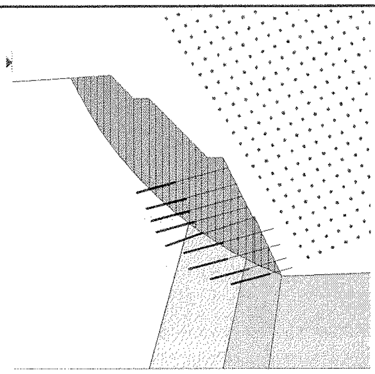


Analytical Models Developed

BISHOP'S METHOD(Circular)

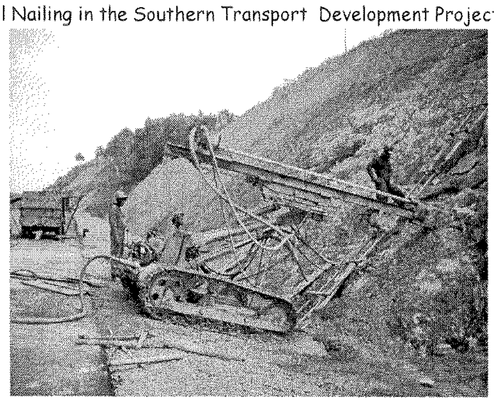


$$F = \frac{\sum \left\{ \left[c'\Delta x_i + (w_i + Q_i - U_i \Delta x_i + T_N \sin\alpha) \tan\phi' \right] \left[\frac{1}{M_i(\theta)} \right] \right\}}{\sum \left[(w_i + Q_i)\sin\theta_i - T_{N,i}\cos(\theta_i + \alpha) \right]}$$



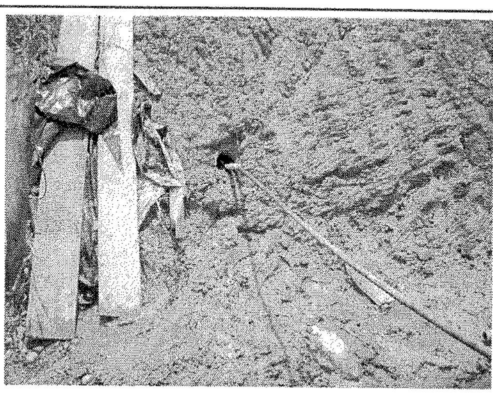
Use of Soil Nailing to stabilize a cut slope

Soil Nailing in the Southern Transport Development Project

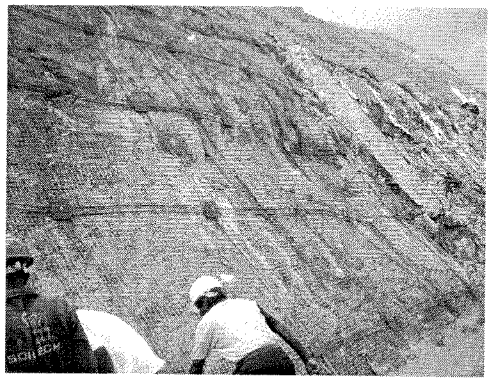


Drilling the hole for the installation of the Nail

10

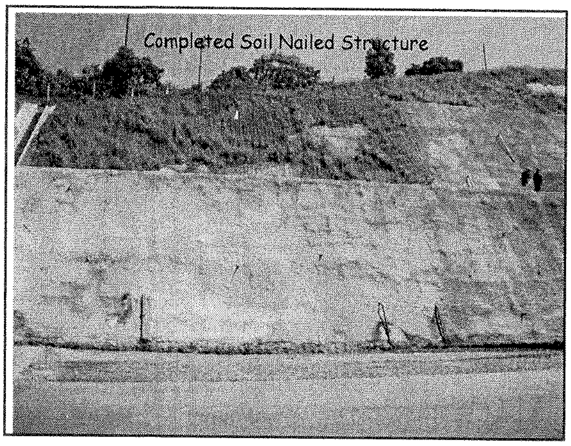


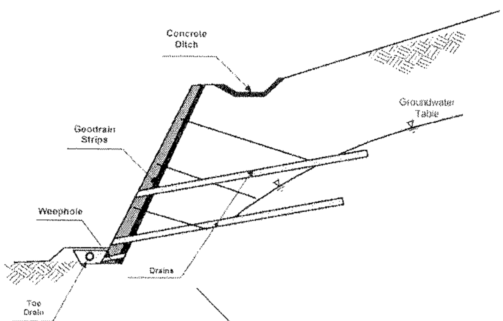
Grouting nearing completion



Anchor Plates and Beams Connecting the nail heads

Shotcreting (Continued)

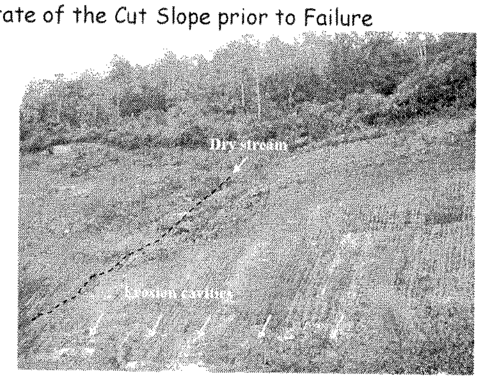




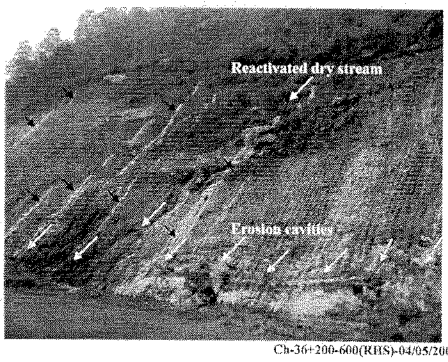
Drainage Of Soil Nail Walls

Landslide at Bogahagoda (Souther part of STDP 36+)

State of the Cut Slope prior to Failure

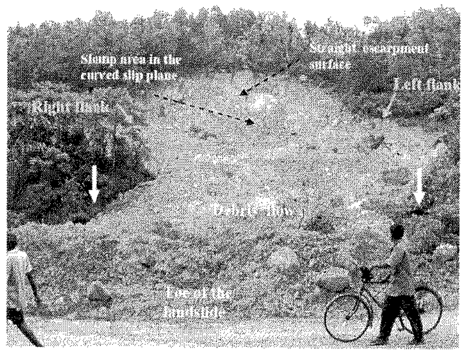


Photograph on a rainy day prior to failure



Ch-36+200-600(RHS)-04/05/2007

After Failure



Another View of the Landslide at 36 +

View of the Right Flank of the Landslide from the Toe

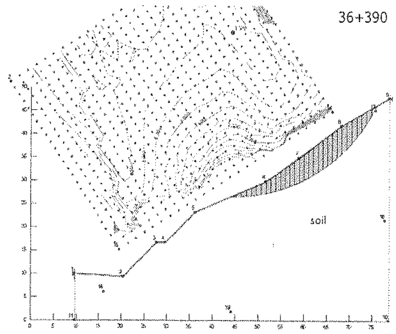
A View of the Left Flank of the Landslide From the Toe

Boulders in the Right Escarpment

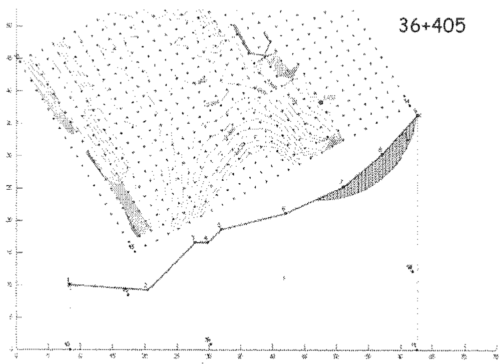
12

Proposal for Rectification

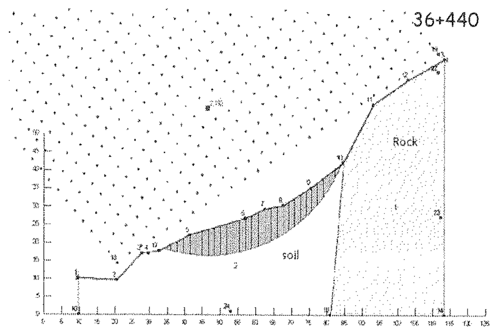
- Control of Drainage - cut off drains and cascade drains
- Rock netting to retain boulders above crest intact
- Soil nailing to retain the slopes at the current steep profile
- Gabion wall at the toe to enhance toe resistance (where necessary)



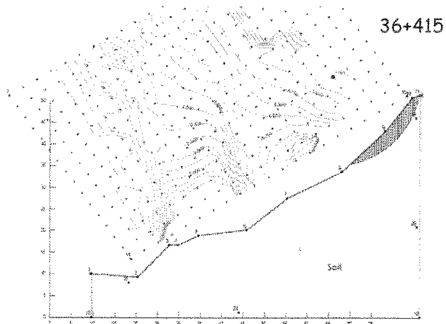
Existing profile is having a sufficient safety margin against failure



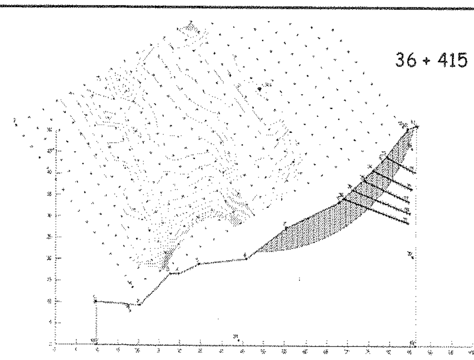
Existing profile is having a sufficient safety margin against failure



Rock ie exposed at the upper level and the existing profile has a sufficient safety margin

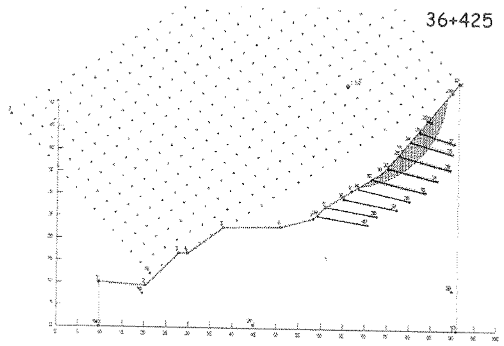


Safety margin of the existing profile is not sufficient. Some stabilization measures are needed at the upper level

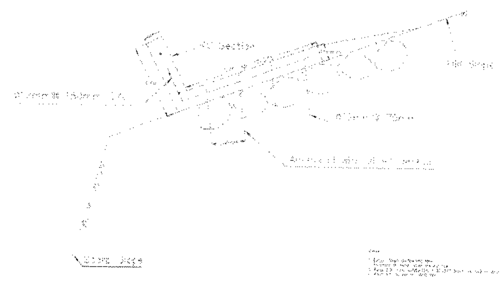


A soil nailing arrangement was proposed at the upper level to enhance the stability

13

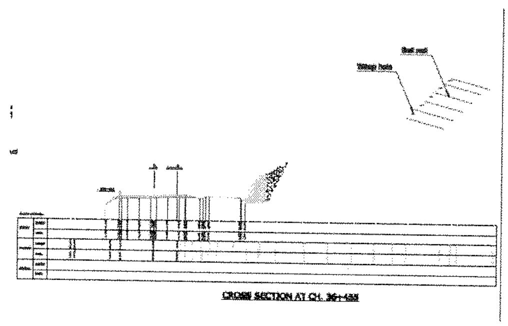


Soil nailing was proposed to enhance the Stability of the slope

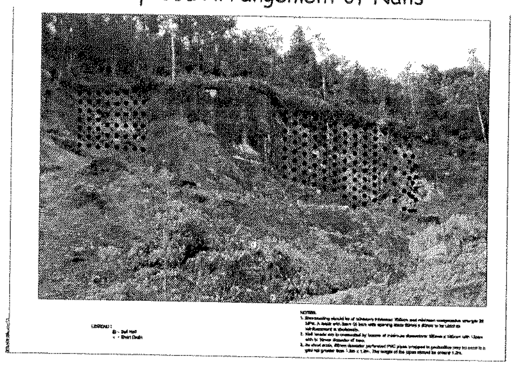


Cut off drain at the crest of the slope

- Has to be done with minimum cutting to minimise disturbance to the boulders at the crest



Proposed Arrangement of Nails



Stability of highway cut slopes can be enhanced by surface and subsurface drainage and use of structural measures

It is essential to monitor all these stabilization measures periodically and attend to whatever the necessary maintenance and repair work promptly

Otherwise,

They will not be able to perform the designed functions.

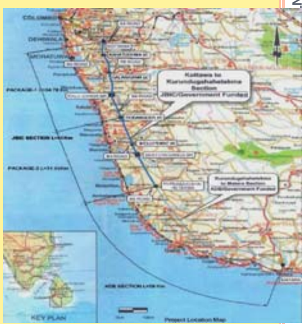
Thank you

Analysis of the Settlement Monitoring Data to Assess the Long Term Performance of the Soft Soil Deposits Subjected to Surcharging

H. S. Thilakasiri
Professor
Department of Civil Engineering
University of Moratuwa

Introduction

- Road traces are very often run through low-lying grounds with soft soil deposits in the subsurface to minimize social issues.
- A common problem with new road embankments constructed in the highly populated western coastal belt of Sri Lanka.
- Construction of high road embankment on such weak compressible grounds to avoid flooding is a major challenge faced by geotechnical engineers.



STDP

Colombo Katunayake Expressway

Outer Circular Highway

Construction of Road Through Soft Soil Deposits

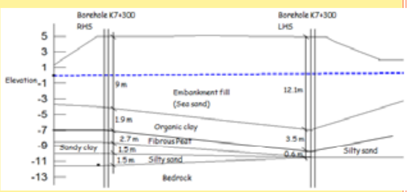
- Preloading and surcharging with or without soft ground treatment is the most cost effective method to improve highly compressible soft soil deposits.
- Other available methods:
  - Replacement of soft soil under the embankment:
    - Only thin deposits can be replaced; and
    - Disposal of the excavated soft (organic) soils.
  - Vacuum consolidation;
  - Construction of the embankment over driven piles;
  - Use of viaducts.
  - Commonly used soft ground treatment methods:
    - Installation of Sand compaction piles/crushed stone piles
    - Installation of prefabricated vertical drains (PVD)

Challenges in Embankment Construction over Soft Soil Deposits

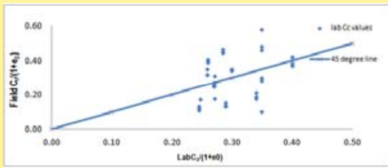
- The stability of the road embankment on very weak ground is a very serious concern during the construction stage ;
  - Excessive settlement leading to cracking; and
  - Slope failure.
- Post construction secondary/primary consolidation settlements pose serious questions regarding the long term serviceability of the road embankment:
  - Cracking leading to failure; and
  - High maintenance cost.

Challenges in Embankment...

- Prediction of the behaviour of soft soil under road embankment during design stage with sufficient confidence level is a major difficulty.
  - Spatial and time variability of the properties of the soft soil over a wide range;
  - Lack of reliable mathematical models predicting the behaviour of the soft soil in Sri Lanka;
  - Changes of the soft soil deposits taking place during construction:
    - Pushing the soft soil to sides (mud waves); and
    - Mixing of fill material and the in-situ soft soil.



Recent investigation showing thick sand layer below the existing level, which cannot be attributed to settlement



Differences in the laboratory measured and back analysed parameters

Parameter	Soil type	Mean	Range
Coefficient of volume compressibility (m^2/MN)	Peat	2.24	0.1 – 7.49
	Organic	1.20	0.2 – 3.70
	Clay	0.68	0.1 – 1.60
Coefficient of consolidation (m^2/year)	Peat	1.69	0.14 – 9.60
	Organic	1.57	0.27 – 8.80
	Clay	2.20	0.44 – 7.10
Modified secondary compression index $[C_\alpha/(1 + e_0)]$ (%)	Peat	-	1.76 – 9.72
	Organic soil	-	1.97 – 4.06
	Clay	-	-

Variability of the consolidation parameters for different soil types in the CKE trace by Hsi et al. (2005)

Challenges in Embankment...

- Any design done has to be modified through the observed behaviour of the embankment during construction stage – 'Observational approach'
- Generally observed parameters:
  - Settlement;
  - Lateral Displacement using inclinometers and/or displacement stakes; and
  - Pore pressure monitoring in the soft soil layer.
- Due to the low cost and the reliability, settlement monitoring is very often done.

Improvement of Soft Soil Deposits by Preloading and Surcharging

- The preloading and surcharging is removed when the soft soil achieves the target degree of consolidation.
- Estimation of the degree of consolidation of the soft soil deposits during preloading and surcharging is an integral part of the ground treatment process.
- In addition, prediction of the long term performance of the embankment based on the observed behavior is essential.
- In this presentation, Analysis of the settlement monitoring data to assess the long term performance of the soft soil deposits subjected to surcharging is done using CKE project as a case study.

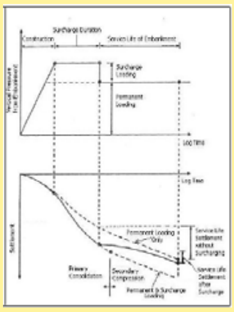
Presentation

- The presentation will be focused on two areas:
- Assessment of the degree of consolidation from the observed settlement monitoring data; and
- Prediction of the long term secondary consolidation behaviour of soil from observed settlement monitoring data.

Degree of Consolidation from the Observed Settlement Monitoring Data

Preloading

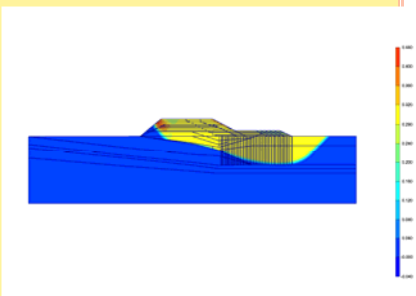
- Preloading generally refers to the process of compressing the soil under a temporary vertical stress prior to construction and then placement of the final structural load.
- The fill load in excess of the service load is referred to as the surcharge load.
- Dissipation of the excess pore water pressure due to filling is very slow.



Advantage of Surcharging

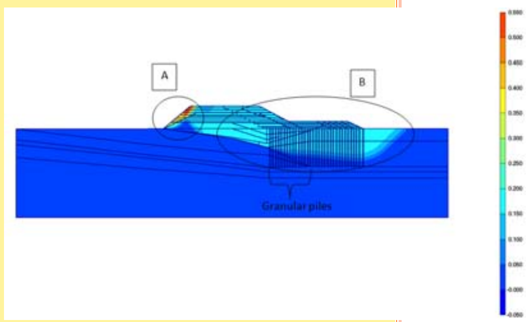
Preloading

- Increased p. w. p. can create unstable embankment slopes.
  - Slow filling rate – step construction
  - Installation of vertical drains to reduce the length of the drainage path.
    - Installation of prefabricated vertical drains (PVD) – only to expedite consolidation NO strengthening effect.
    - Installation of sand compaction piles (sand columns) or crushed stone piles (gravel compaction piles) – to expedite consolidation and strengthening of the soft soil.

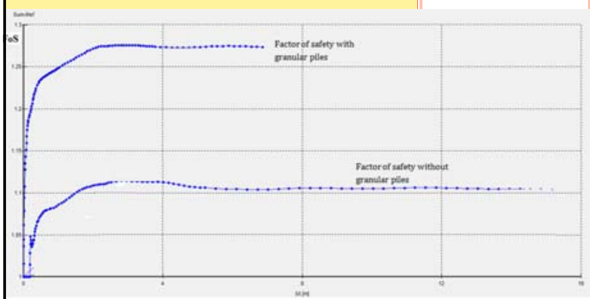


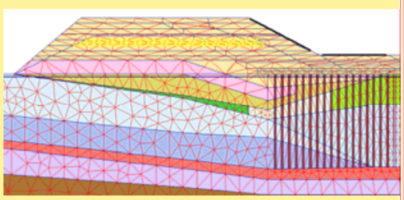
FEM analysis of an embankment over soft soil without SCP (FoS minimum is 1.1)

FEM analysis of an embankment over soft soil with SCP (FoS minimum is 1.27)



FoS with and without granular piles





FEM mesh with granular piles

Settlement Analysis to Establish the DoC

- Even though there are large number of methods available to determine the DoC of soft soil deposits, most widely used methods are:
  - Asaoka method; and
  - Hyperbolic method.
- Ariyarathne and Thilakasiri (2011) after analysis of settlement monitoring data, pore pressure measurements and lab consolidation test results conducted in the Southern Expressway project concluded that:
  - Asaoka Method is reasonably accurate and it can be used to estimate the ultimate primary consolidation settlement of cohesive soils.

Loca-tion	Degree of Consolidation (%)		
	Asaoka Method	Laboratory Data	PWP
45+405	97.83	83.10	79.5
A1 - 1	99.20	79.94	100.0
A1 - 2	99.10	79.24	100.0
A2	97.10	100.00	100.0
B2 - 1	98.06	100.00	100.0
B2 - 2	98.60	100.00	100.0
C1 - 1	96.80	58.47	97.83
C1 - 2	95.40	68.09	64.05
52+970	97.57	90.91	100.0
53+690	96.65	96.70	68.71

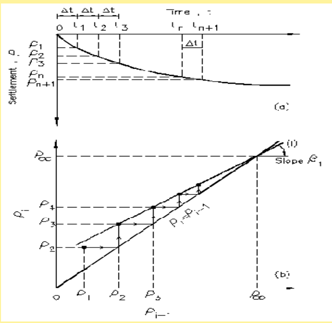
From Ariyarathne & Thilakasiri (2011)

Results from Ariyarathne & Thilakasiri (2011).......

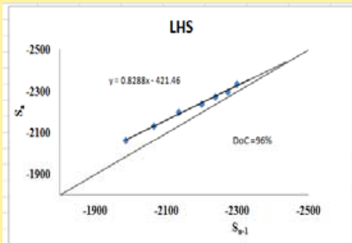
- All the sections considered in Ariyarathne & Thilakasiri (2011) were improved using Compacted Vacuum Consolidation (CVC) method.
- The DoC from Asaoka method slightly overestimate compared to PWP measurement and Lab test results.

Asaoka Method

- Step 01:
  - The observed time settlements curve is plotted to an arithmetic scale and is divided into equal time intervals, Δt. The settlements $\rho_1, \rho_2, \rho_3, \ldots\ldots \rho_i$ corresponding to time $t_1, t_2, t_3 \ldots\ldots t_i$.
- Step 02:
  - The settlements values ρ_1, ρ_2, ρ_3 plotted as points (ρ_{i-1}, ρ_i) in a coordinates system with axis ρ_{i-1}, and ρ_i as shown in Figure 1 the 45^0 line $\rho_{i-1} = \rho_{iis}$ also drawn.
- Step 03:
  - A straight line (I) is fitted through the data points. The point where, this line intersect the line gives the final consolidation settlement (ultimate primary settlement).



Asaoka plot



Typical Asaoka plot from the CKE project

Hyperbolic Method

- Tan (1971) made use of the hyperbolic method to predict settlement of clay undergoing secondary compression.
- Chin (1975) also made use of the hyperbolic to predict settlement due to both primary and secondary compression.
- Thilakasiri (2011) showed that the Hyperbolic method underpredict secondary consolidation settlement of peaty soils.

Hyperbolic Method

- According to the hyperbolic method of estimation of the primary consolidation settlement, the settlement (S) and the elapsed time (t) follow the hyperbolic relationship given below].

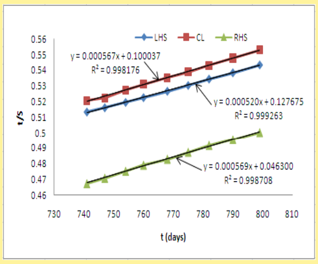
$$S = \frac{t}{\alpha t + \beta}$$

- Where α and β are constants. Assuming that the above settlement vs time variation continues in the future, it is possible to show that the final primary consolidation settlement is equal to 1/α.
- Rearranging the terms in the above relationship, one could obtain the linear relationship between (t/S) vs t given below.

$$\frac{t}{S} = \alpha t + \beta$$

Hyperbolic method

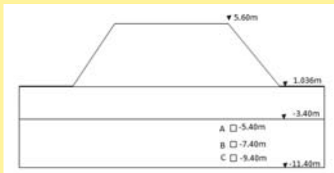
- Based on a series of laboratory consolidation test results, Al-Shamrani (2005) showed that:
  - Initial linear portion of t/S vs t curve can be used to estimate the ultimate primary consolidation settlement; and
  - linear portion of t/S vs t curve, BEYOND 90% DoC can be used to estimate the final settlement including secondary consolidation settlement.
- For soils, which exhibit prominent secondary compression behaviour, Al-Shamrani (2005) proposed to use hyperbolic method only in estimation of ultimate primary consolidation settlement.



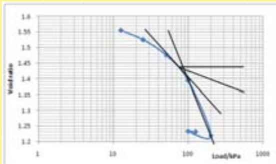
Typical initial linear t/S vs t variations

Field and laboratory testing programme

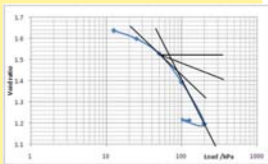
- A field testing programme was conducted in the CKE project to establish the soil profile and the preconsolidation pressure of the soft soil at selected sections.
- Using the settlement monitoring data, the final primary consolidation settlements at the tested locations were determined using both hyperbolic method and Asaoka method.
- The estimated final primary consolidation settlement was used to estimate the degree of consolidation (DoC) of the soft soil.



Locations of the soil samples and their preconsolidation pressure



Sample from 11m depth



Sample from 13m depth

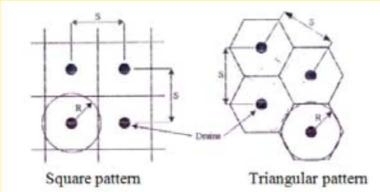
Location	Final primary consolidation settlement (mm)	Present settlement (mm)	Degree of consolidation (%)
K 5 + 400	2042	1976	97
K 7 + 300	1520	1486	98
K 5 + 550	2370	2179	92
K 5 + 420 ()	2090	1918	92
K 7 + 350	1055	1283	100

DoC from Asaoka method

Location	Final primary consolidation settlement (mm)	Present settlement (mm)	Degree of consolidation (%)
K 5 + 400	2736	1965	72
K 7 + 300	1887	1454	77
K 5 + 550	3264	2160	66
K 5 + 420 (T)	1976	1133	57
K 7 + 350	1716	1237	72

DoC from the Hyperbolic method

20



Plan view of the soft ground treated with SCP/CSP

Stress distribution in soft soil layers treated with CSP or SCP

If the total stress increment at any level of the treated ground is $\Delta\sigma_T$, the stress increment on the soft soil is $\Delta\sigma_c$ and the same in SCP or CSP is $\Delta\sigma_S$.

Considering a unit cell, the total area, A may be expressed as given below:

$A = A_s + A_c$ [7]

The area ratio, a, is defined as

$a = \frac{A_S}{A}$

Considering total stress on the soil layer, Eq. [8] could be written considering the vertical equilibrium.

$A\Delta\sigma_T = A_s\Delta\sigma_s + A_c\Delta\sigma_c$ [8]

From Eq. [7],

$\frac{A_C}{A} = 1 - a$ [9]

Stress distribution in soft soil layers treated with CSP or SCP

From Eqs. [8] and [9]

$\Delta\sigma_T = a\,\Delta\sigma_s + (1-a)\Delta\sigma_c$ [10]

$\frac{\Delta\sigma_S}{\Delta\sigma_c} = n$ (Stress concentration factor)

$\Delta\sigma_c = \frac{\Delta\sigma_T}{a(n-1)+1}$ [11]

$a = \frac{\pi}{4}\left(\frac{D}{S}\right)^2$ for square pattern

$a = \frac{\pi}{2\sqrt{3}}\left(\frac{D}{S}\right)^2$ for triangular pattern

$\Delta\sigma_T$ = Total stress increment

$\Delta\sigma_s$ = Stress increment on SCP

$\Delta\sigma_c$ = Stress increment on soft soil

A_s = Area of SCP or CSP

A_C = Area of soft soil within a unit cell

A = Total area of a unit cell

D = Diameter of SCP or CSP

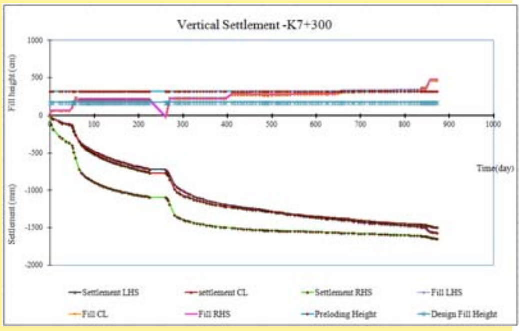
S = Spacing of SCP or CSP

Comparison of DoC from different methods

Location	Stress concentration factor	DoC from laboratory testing	DoC from Asaoka method	DoC from Hyperbolic method
K 5 + 400	1	47	97	72
	3	53		
	5	69		
K 7 + 300	1	38	98	77
	3	44		
	5	62		
K 5 + 550		64	92	66
K 5 + 420 (T)		31	92	57
K 7 + 350		22	100	72

Discussion

- Samples were obtained from thin wall samples.
- Soft soil at K 7 + 300 and K 7 + 350 had two distinctly different soil types: organic clay and fibres peat.
- The LHS settlement at the two sections K 7 + 300 and K 7 + 350 show almost linear settlement rate over a long period of time.
  - At K 7 + 300 – treated with SCP; and
  - At K 7 + 350 – no soft ground treatment
- A stress concentration factor of 5 yields the DoC from lab preconsolidation pressure close to the DoC from Hyperbolic method.
- Asaoka method overpredicts the DoC compared to the DoC from lab preconsolidation pressure.



PREDICTION OF THE LONG TERM SECONDARY CONSOLIDATION BEHAVIOUR OF SOIL FROM OBESERVED SETTLEMENT MONITORING DATA

INTRODUCTION

- The secondary consolidation settlement of the embankment during project liability period should be estimated to assess the long term behavior of the embankment.
- The secondary consolidation settlement is generally estimated using the log time method.
- Log-time method assumes:
  - that the variation of the secondary consolidation settlement (S_s) follows a linear variation with the log of the elapsed time; and
  - the secondary consolidation starts after the end of primary consolidation settlement.

Log – time method

- The relationship between the secondary consolidation settlement (S_s) and the time (t) is expressed by:

$$S_s = \frac{HC_\alpha}{1+e_0} log\left[\frac{t}{t_p}\right]$$

- Where H, C_α, e_0, and t_p are the thickness of the soft soil layer, coefficient of secondary compression, initial void ratio and the time taken for the end of primary consolidation settlement respectively.

USE OF THE LOG-TIME METHOD IN ASSESSING THE EFFECTS OF OCR

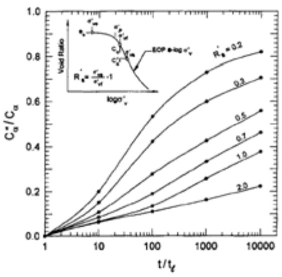
- based on the results of the laboratory experiment, Mesri et al. (1997) had developed set of curves illustrating the dependency of the compression index C_α on the surcharging ration

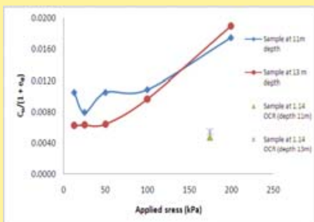
$R_s^/ = (\sigma_{vs}^/ / \sigma_{vf}^/) - 1$

  - $\sigma_{vs}^/$ is the maximum effective vertical stress reach before removal of the surcharge and
  - $\sigma_{vf}^/$ is the final effective vertical stress after removal of the surcharge.

USE OF THE LOG-TIME METHOD IN ASSESSING THE EFFECTS OF OCR

- The ratio between the coefficient of secondary consolidation after removal of the surcharge, $C_\alpha^{//}$, to the original coefficient of secondary consolidation, C_α, is related to $R_s^/$ depending on the (t/t_i) as shown



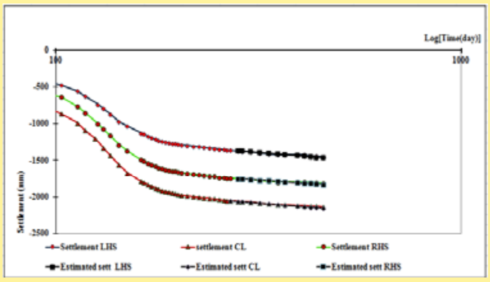


Reduction of C_α due to OCR from lab testing in CKE project

22

Prediction of the secondary consolidation settlement

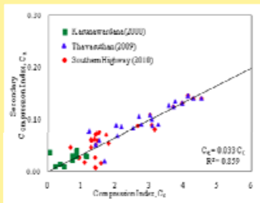
- Two approaches can be used to estimate the secondary consolidation settlement depending on whether the primary consolidation is over (or at least 90% over):
  - If the primary consolidation is over, the secondary consolidation settlement of the embankment may be calculated from the settlement monitoring data assuming a linear variation of settlement vs. log(time); and
  - If the primary consolidation is ongoing, laboratory determined coefficient of secondary consolidation (C_α) may be used to estimate the secondary consolidation settlement.



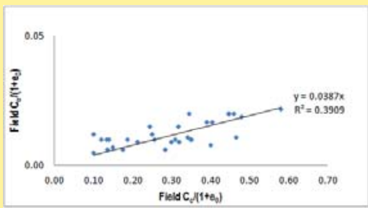
Prediction of the long term secondary consolidation settlement from the settlement monitoring data

Comparison of the back analysed consolidation parameters

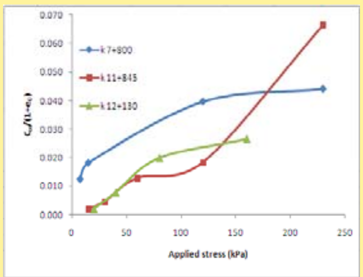
- Mesri et al. (1997) showed that there is a correlation between laboratory $C_c/(1 + e_o)$ and laboratory $C_\alpha/(1 + e_o)$.
- Ariyarathne & Thilakasiri (2011) and Karunawardane et al. (2000) showed that a similar relationship exists between the laboratory consolidation results for Sri Lankan peaty soil.
- The $C_c/(1 + e_o)$ and $C_\alpha/(1 + e_o)$ of the soft soil deposits were back analysed using field settlement monitoring data as explained above for untreated soft soil deposits.
- A fairly good correlation similar to one proposed by Mesri et al. (1997) exists between field parameters as well.



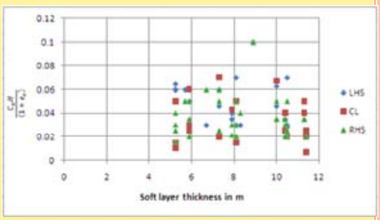
Field C_c and C_α



Field $C_c/(1 + e_o)$ and $C_\alpha/(1 + e_o)$ for untreated soft soil deposits



laboratory determined coefficient of secondary consolidation from CKE project



Variation of the back analysed C_α with the thickness of the soft layer

Conclusions

- Ariyarathne and Thilakasiri (2011) based on data analysis from vacuum consolidated sections of the Southern Expressway project concluded that the Asaoka Method is reasonably accurate and it can be used to estimate the ultimate primary consolidation settlement of cohesive soils.
- However, from the analysis of data from the treated (with SCP and CSP) and untreated soft grounds from CKE project indicates that the Asaoka method overestimates the DoC. Extension of the ongoing research project is planned to investigate this further.

Conclusions

- The use of the hyperbolic method to estimate the final primary consolidation settlement of peaty soils is promising but requires more data to draw solid conclusions.
- The stress concentration factor of about 5 seems to fit the hyperbolic analysis with the laboratory determined soil parameters.

Conclusions

- A fairly good correlation similar to one proposed by Mesri et al. (1997) exists between back analysed field $C_c/(1 + e_o)$ and $C_\alpha/(1 + e_o)$ parameters for untreated soft soil deposits.
- The $C_\alpha/(1 + e_p)$ of the normally consolidated organic soil is in the rage of 0.01 to 0.07; and
- There is a significant reduction in $C_\alpha/(1 + e_p)$ as the soil becomes overconsolidated.
- The back analysed $C_\alpha/(1 + e_o)$ values are in the same range as those obtained from laboratory testing.

THANK YOU !!!!!

Ground Improvement in Road Projects – Australian Experience

Jayantha Ameratunga

Coffey Geotechnics/National Building Research Organisation

1.0 Introduction to Ground Improvement

Accelerated development worldwide over the last few decades has seen increasingly marginal lands being used for residential, industrial and commercial developments as well as for infrastructure that is needed to cater for the increasing needs and population increases. Construction on marginal lands invariably requires the improvement of the ground to satisfy the performance criteria expected in the designs. Ground improvement therefore has been given significant attention by the Governments, clients, consultants, academia, researchers as well as the contractors because of the risks associated with design and construction and the consequences of failure plus the exorbitant costs that could be involved in improving the ground.

Civil engineers now consider ground improvement generally on a routine basis although the knowledge they receive is usually after graduation, i.e., when practising in the industry, because insufficient attention is given to ground improvement in University or Technical courses except for the standard preloading/surcharging. There are many aspects requiring deep knowledge of ground improvement before implementation, both in design and construction. On the design aspects of ground improvement, considerable research had been done by academics and practising engineers, sometimes collaboratively, and significant advances have been made. However, there is still a significant amount of empiricism built into the design of many a technique and therefore the Observational Method (Peck, 1969) is consistently used by the industry on significant projects. Construction has also improved leaps and bounds with development of new machinery and the use of modern techniques. However, some methods still require considerable skill and therefore experienced operators. Ground improvement would be feasible not only if soil type is amenable to improvement in performance but only if sufficient expertise, time and equipment are available, and if economically feasible.

2.0 Ground Improvement – Main Functions and Types available

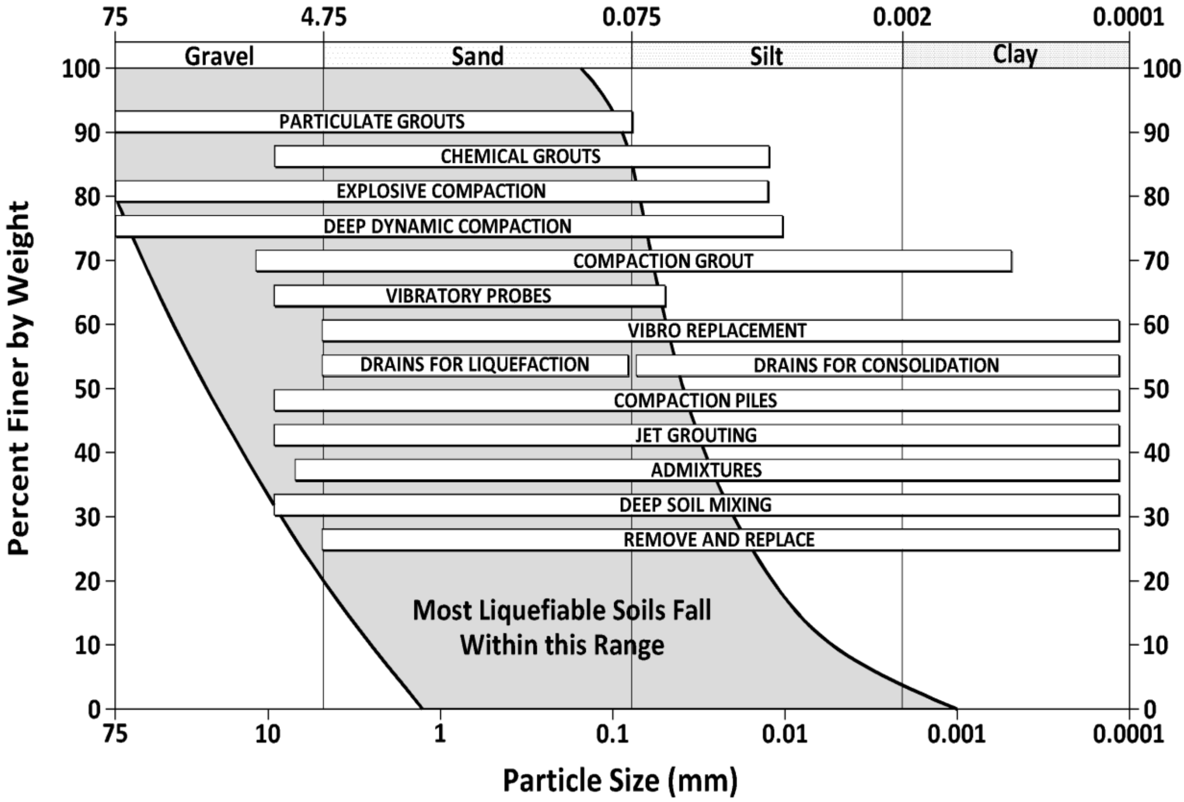
The main functions of ground improvement could be summarised as follows and the metods presented in Table 1 as well as Figure 1 (ref 2):

- Increase bearing capacity
- Increase density
- Increase strength
- Transfer loads
- Control deformations
- Accelerate consolidation
- Decrease imposed loads
- Increase lateral stability
- Form seepage cutoffs or fill voids
- Increase liquefaction resistance

Table 1: Function and Methods of Ground Improvement

Category	Function	Methods
Densification	Increase density, bearing capacity, and frictional strength; increase liquefaction resistance of granular soils; decrease compressibility, increase strength of cohesive soils	Vibrocompaction Dynamic compaction Blasting compaction Compaction grouting Surface compaction (including rapid impact compaction)
Consolidation	Accelerate consolidation, reduce settlement, increase strength	Preloading without drains Preloading with vertical drains Vacuum consolidation Electro-osmosis
Load Reduction	Reduce load on foundation soils, reduce settlement, increase slope stability	Geofoam Foamed concrete Lightweight fills, tire chips, etc. Column supported embankments with load transfer platforms
Reinforcement	Inclusion of reinforcing elements in soil to improve engineering characteristics; provide lateral stability	Mechanically stabilized earth Soil nailing/anchoring Micro piles Columns (aggregate piers, stone columns, jet grouting, etc.) Fiber reinforcement Geosynthetic reinforced embankment
Chemical Treatment	Increase density, increase compressive and tensile strength, fill voids, form seepage cutoffs	Permeation grouting with particulate or chemical grouts Bulk infilling Jet grouting Compaction grouting Deep soil mixing-wet and dry Fracture grouting Lime columns
Thermal stabilization	Increase shear strength, provide cutoffs, reduce liquefaction potential	Ground freezing Ground heating and vitrification
Biotechnical stabilization	Increase strength, reinforcement	Vegetation in slopes as reinforcing Microbial methods
Miscellaneous	Remediate contaminated soils	Electrokinetic methods, chemical and bio-chemical methods

Figure 1 – Available Ground Improvement Methods for Various Soil Types



2.1 Web Based System to Select Ground Improvement Type

The above list provides a snapshot of the options available for ground improvement. Therefore it is not an easy task to select the most appropriate ground improvement project for a site/project. A project has been launched in USA to provide valuable information and guidance to select ground improvement method/s and given below is a brief introduction using the contents of the State of the Art paper (ref 2).

The second Strategic Highway Research Program (SHRP 2) was created by US Congress in 2006 to address challenges in transportation in the highways and geotechnical issues are addressed in SHRP 2 Renewal Focus Area, in which the goal is to develop a consistent, systematic approach to the conduct of highway renewal that is rapid, causes minimum disruption, and produces long-lived facilities. The SHRP 2 R02 project is aimed at identifying geotechnical solutions for three elements:

1) Construction of new embankments and roadways over unstable soils
2) Widening and expansion of existing roadways and embankments, and
3) Stabilization of the working platform through a project titled: *Geotechnical Solutions for Soil Improvement, Rapid Embankment Construction, and Stabilization of the Pavement Working Platform.* to anyone contemplating ground improvement to

The R02 research team identified and narrowed down the number of technologies for ground improvement as shown in Table 2. For each of them a comprehensive technical summary including the current state of the practice of design, QC/QA, costs and specifications were developed. The results are set up on a web based system that is user-friendly and targeting the geotechnical personnel from all walks of life.

Table 2: Ground Improvement Methods covered by the web based system

Aggregate Columns	Excavation & Replacement	Mechanical Stabilization of Subgrades & Bases
Beneficial Reuse of Waste Materials	Fiber Reinforcement in Pavement Systems	MSE Walls
Bio-Treatment for Subgrade Stabilization	Geocell Confinement in Pavement Systems	Micro-Piles
Blast Densification	Geosynthetic Reinforced Construction Platforms	Onsite Use of Recycled Pavement Materials
Bulk-Infill Grouting	Geosynthetic Reinforced Embankments	Partial Encapsulation
Chemical Grouting/ Injection Systems	Geosynthetic Reinforcement in Pavement Systems	PVDs & Fill Preloading
Chemical Stabilization of Subgrades & Bases	Geosynthetic Separation in Pavement Systems	Rapid Impact Compaction
Column-Supported Embankments	Geosynthetics in Pavement Drainage	Reinforced Soil Slopes
Combined Soil Stabilization with Vertical Columns	Geotextile Encased Columns	Sand Compaction Piles
Compaction Grouting	High-Energy Impact Rollers	Screw-In Soil Nailing
Continuous Flight Auger Piles	Hydraulic Fill + Vacuum Consolidation + PVDs	Shoot-In Soil Nailing
Deep Dynamic Compaction	Injected Light-Weight Foam Fill	Shored MSE Walls
Deep Mixing Methods	Intelligent Compaction	Traditional Compaction
Drilled/Grouted & Hollow Bar Soil Nailing	Jet Grouting	Vacuum Preloading w/ & w/o PVDs
Electro-Osmosis	Light Weight Fills	Vibrocompaction

3.0 Ground Improvement Methods frequently used for Road Projects

Ground improvement methods frequently used for road projects could be categorised as follows:

1. Civil engineering solutions
2. Removal of weak soils
3. Densification
4. Consolidation
5. Modification
6. Load transfer
7. Weight reduction

3.1 Civil Engineering Solutions

Civil engineering solutions include:

a) Do nothing approach - If the client is happy to manage with the performance without ground improvement this is perhaps the most economical method in the shortterm. For temporary roads this type of approach is acceptable if the settlements are not significantly high. However, road authorities have fairy stringent performance criteria even for temporary roads and therefore it is difficult to implement a Do Nothing strategy very often.
b) Move alignment to avoid difficult ground - This is one of the first options that come to the designer's mind once the distribution of weak soils is understood. Unless the project is at planning stage or the approved road corridor is sufficiently wide, it is difficult shift an alignment as environmental impact studies have to be re-done and approval sought which could delay the project.
c) Lower alignment to reduce stresses on the ground – By lowering the alignment the imposed loads on the ground would be less thereby reducing the expected settlements under the road embankment. This is most useful when the compressible clays are found to be slightly overconsolidated and by reducing the imposed stresses the effective stresses within the soil mass would not increase beyond the pre-consolidation pressure i.e. significantly less settlements than if the subsoils were stressed to a normally consolidated state.

3.2 Removal of weak soils

Removal of weak soils is quite common on road projects especially when the excavation is shallow. Depending on the project and the subsoil conditions even this simple form of ground improvement could become very expensive. The costs increase significantly if the excavated soils have to be removed to remote sites and/or if the soils are contaminated or possible acid sulphate and therefore treatment would be required. If the treated souls could be reused the costs could be recovered.

Another method of weak soil removal is known as mud waving. In mud waving, the ground is subject to a heavy fill load until the weak soils become plastic and start to flow creating a mudwave. The method needs greater control than routine excavation and there are risks involved in mud wave creation as well as the entrapment of mud.

Removal of weak soils is generally limited to remove layers having small thicknesses.

3.3 Densification

Impact roller is frequently used to densify shallow soils. It is understood that impact rolling has been successfully applied both clayey and sandy fill as well as waste materials and building rubble. The depth of improvement is understood to be less than 2m for clays but greater for cohesionless materials and other types of fill materials.

Dynamic compaction is carried out by dropping a heavy pounder, 6 to 30 tons, over heights as high as 25m to 30m. The free fall of the pounder creates stress waves which allows densification of the soils. The technique is most effective in granular soils. Depth of improvement varies but studies have suggested depths over 10m

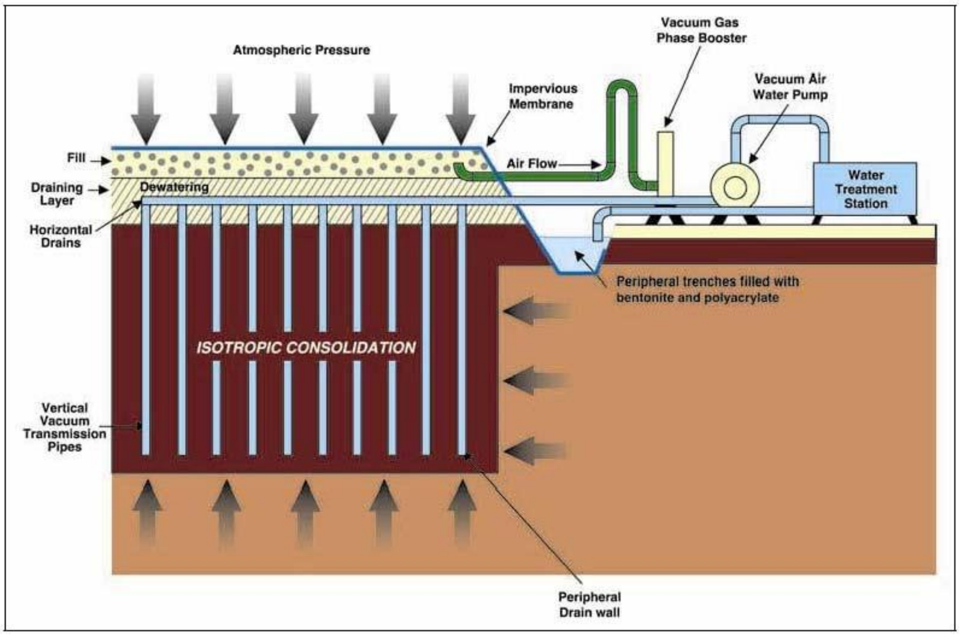
3.4 Consolidation

Ground improvement types adopted to accelerate consolidation include:

a) Preloading/surcharging – with or without wick drains
b) Vacuum consolidation (membrane and non-membrane types)
c) Electro-osmosis

Preloading/surcharging is one of the most frequently used ground improvement techniques. It is also found to be relatively cost effective. There is a significant amount literature on the subject as research has been widely carried out by universities as well as the industry.

Vacuum consolidation was introduced to Australia only recently. The first ever trial was conducted at the Ballina Bypass project where a settlement of over 5m was recorded under the area subjected to Menard type vacuum. Another Australian first occurred when Port of Brisbane also carried out a trial with the inclusion of a deep cutoff wall using soil-bentonite mix. The trial at this site was successful which allowed the client to extend the vacuum area soon after the trial was completed. The advantages in the vacuum system is the reduction in lateral movement and therefore increased rate/height of embankment construction and the rapid consolidation in the early stages allowing for faster rates of fill placement.

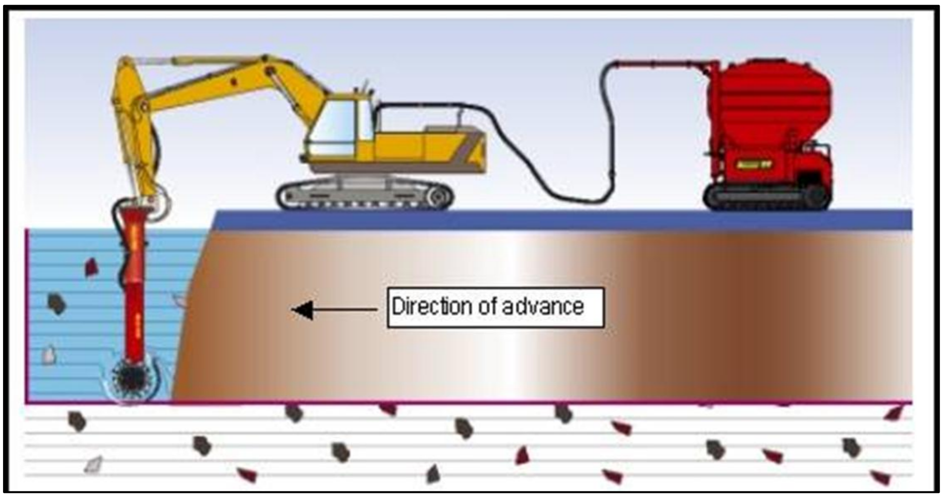


Electro-osmosis, although a relatively old method of ground improvement, has not been done in Australia. So far not even a trial has been carried out possibly because of the significantly high costs involved.

3.5 Modification

Some of the modification methods used in road projects are:

a) Mass stabilisation (lime or cement)
b) Lime piles (composite effect)
c) Grout injection (generally for granular soils)
d) Various [Ground freezing (temporary), Bio-treatment (biogrout, Smart Soils)]

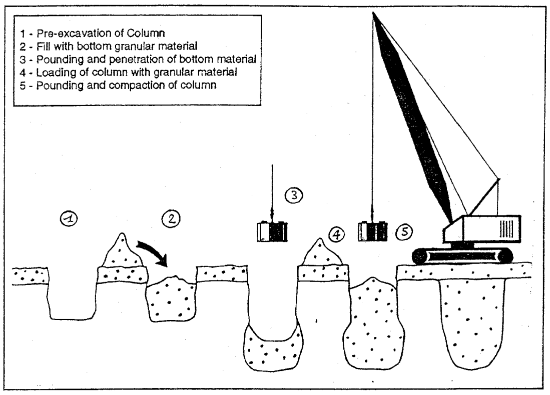


3.6 Load Transfer

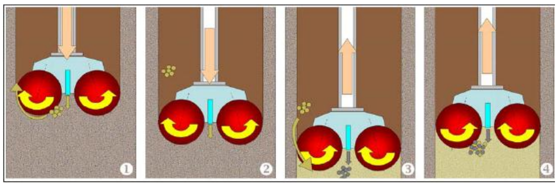
Load transfer techniques include:

- Semi-rigid inclusions (stone columns, dynamic replacement)
- Deep soil mixing (dry, wet, CSM, turbo jet)
- Rigid inclusions – displacement concrete columns or controlled modulus columns
- Piled embankments/piled rafts

Dynamic replacement is more frequently used because it is a relatively cheap compared to stone columns or similar. This is because lower quality materials could be used instead of sound rock as fill materials. At least a nominal preload should be applied to areas improved by dynamic replacement to obtain better performance. Monitoring of such preload would also allow any adverse behaviour to be remedied.

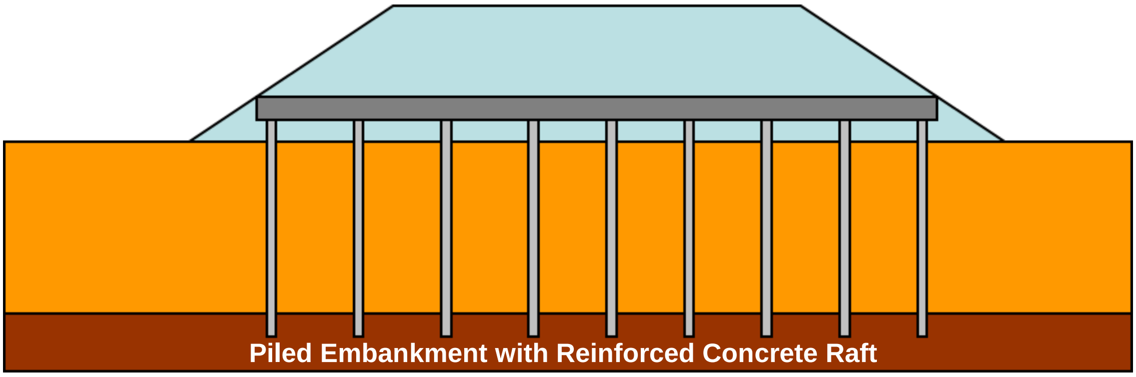


Deep soil mixing has penetrated the Austrlian market in the recent past especially on road projects, specifically on bridge approaches or similar where tighter control of settlements is required. One of the most commonly used techniques is the Cutter Soil Mixing (CSM). and more use of this technique on road projects (dry, wet, CSM, turbo jet)



Other types of load transfer techniques include:

a) Piled embankment with reinforced Concrete raft
b) Piled Embankment with Geosynthetic Reinforced Gravel Mattress
c) Embankments Supported Using Controlled Modulus Columns (CMC) or Displacement Augered Columns (DAC



3.7 Weight Reduction

The weight imposed by the road embankment could be reduced and therefore expected settlements by the use of:

- Light-weight fill (bottom ash, pumice, light-weight concrete)
- Ultra light-weight fill (Expanded Polystyrene Blocks)

Bottom ash weighs 1300 to 1400kg/m3 and the ultra light-weight at least one order less. The latter is significantly more expensive and therefore only used only at critical locations. The Port of Brisbane Motorway included two abutments of a bridge constructed using polystyrene blocks.

REFERENCES/BIBILIOGRAPHY

1. Mitchell, J K & Wong, P K W (2011). Coffey Internal seminar
2. Schaefer, V R, Mitchell, J K, Berg, R R, Filz, G M and Douglas, S C (2011). Ground Improvement in the 21st Century: A comprehensive Web-Based Information System. Geotechnical Engineering State of the art and Practice. ASCE Geotechnical Special Publication No 226. Geotechnical Engineering State of the Art and Practice, Keynote Lectures from GeoCongress 2012.
3. Ameratunga, J., Boyle, P., De Bok, C. and Berthier, D. (2010). Ground Improvement in Port of Brisbane (PoB) clay. ISSMGE Bulletin, Vol 4, Issue 2, June 2010, pp 28-54.