RTSA

STABILISATION OF RAIL TRACK FORMATION AND EMBANKMENTS

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SUMMARY

Great improvements in Rail track technology have been achieved in recent years, especially in the fields of ballast specification, sleeper design, rail weight increase, rail profile maintenance by grinding, rail-wheel interfacing and suspension improvements to rolling stock.

As a result trains are running faster, with greater axle loads and at an increasing frequency as the demands for carriage of raw materials to port for export and general freight continually increase.

Yet with all these improvements, speed restrictions on discrete sections of track are still a major cause of frustration to the scheduled running of trains.

One of the major causes of these speed restrictions is attributable to the failure of the track formation to adequately support the track infrastructure and the rail traffic thereon. Often this failure is caused by variations in moisture levels in the clay formation subgrade, which lead to shrink and swell of reactive clays and shear failure of saturated clays.

These problems can be rectified by Slurry Injection Stabilisation of the clay formation and subgrade, whereby cementitious slurry is pumped under pressure into the subgrade from a hi-rail vehicle without the need to remove and replace track infrastructure.

1 INTRODUCTION

This paper reports on work undertaken by QR to rehabilitate existing rail track formation using Slurry Injection Stabilisation at an economically sustainable price and in a manner having a minimal disruption to their core business of running trains. The process of Slurry Injection Stabilisation is able to be undertaken without the removal of track infrastructure and between scheduled train paths.

1.1 What is the problem?

QR Infrastructure Group currently maintains 1357 route kilometres of heavy haul track of which greater than 70% were constructed in excess of 25 years ago with the earliest, Rockhampton to Blackwater being opened in July 1877. Up until the early 1960s formations were compacted to no set standard and compaction was left to consolidation over time.

Selection of materials for construction of embankments was by the process of using the closest available material at hand. In the flat black soil plains this invariably involved excavation of a borrow pit and utilising the expansive soil therein.

No specific sub-ballast layer was incorporated in the top of the fill or cutting to isolate the ballast from the underlying clay formation.

Drainage of the track easement presented significant problems in that the very flat nature of the blacksoil plains made it difficult to run water away from the railway easement.

With the onset of wet weather, precipitation percolated down through the ballast and ponded in the railway cess, wetting the clay formation. As a result, the clay softened, ballast was pushed down into the formation and water started to pond. Fines were "pumped" out of the clay as trains passed and ballast was pushed deeper and deeper into the formation. With time ballast pockets formed at increasing depth which allowed moisture to penetrate deeper and deeper into the formation, saturating and weakening the bearing capacity of the clay formation.

In clays exhibiting volumetric instability, shrinking and swelling is caused by soil moisture variations. Moisture penetrating into the formation causes the soils to swell.

Conversely as soils dry out they shrink, however this swell and shrink cycle is not even in the longitudinal and lateral aspect of a railway track. This results in dips and hollows along a longitudinal section of the track. In the lateral aspect of the track, one rail becomes higher or lower than the other in a random pattern.

As a consequence, train speeds have to be restricted in these areas, which as aforementioned, disrupts the scheduled running of trains.

1.2 Treatment alternatives

1.2.1 Ballasting

Ballasting and tamping is where ballast is added and tamped to lift the lowest point in the track up to the required level to create a smooth running surface. This mode of treatment is relatively quick to perform however it does not treat the cause of the problem. Hence it becomes a repetitive process and with time lifts the track infrastructure higher and higher above the design level.

Lateral track stability is reduced as lateral support to rail structure from the ballast shoulder at the extremity of the sleepers lessens and ballast falls away to adopt its natural angle of repose. This increases the " buckle " potential of the track structure. In addition:

- The height between top of rail and the overhead electric traction wire is reduced (if present).
- Grade changes are introduced as track meets fixed structures such as transom deck or ballasted deck bridges.
- Ballast life is reduced by the process of increased tamping.

1.2.2 Reconstruction

Reconstruction of the track formation is where trains are stopped from running and rails, sleepers and ballast are removed. The formation is excavated and dumped, while new quarry sourced material is placed and compacted, often in conjunction with geotextile fabrics. The rail, sleeper and ballast infrastructure is then replaced.

This method is an effective remedy however it is very expensive and disruptive to train operations and often causes further problems at its extremities due to the difference in modulus (flexibility) between it and the un-reconstructed sections it adjoins.

1.2.3 Drainage

Drainage of the site is of paramount importance and the use of French drains and graded swales to get moisture away from the track vicinity will help to reduce the moisture changes in the soils. However where volumetrically unstable expansive clays exist, water percolating down through the ballast and natural moisture movements in the soil will still cause instability.

1.2.4 Mechanical stabilisation

Mechanical lime or cement stabilisation of the top 300-400mm of the formation is very effective in creating a moisture impervious sub ballast layer which won't soften upon wetting, will support the ballast and can be graded to shed water to cess drains.

However it requires the stopping of traffic for major track closures with the removal and subsequent replacement of rails, sleepers and ballast. In areas where expansive clays exhibit volumetric instability some distortion of the track running surface will occur.

1.2.5 Slurry injection stabilisation

Slurry Injection stabilisation of rail track formation is a process where cementitious slurry of lime and flyash is pumped under pressure from a hi-rail mounted vehicle, through slowly descending hollow probes pushed into the clay subgrade. The slurry is laterally dispersed from the probe tip into the surrounding clay formation and subgrade.

A random network of slurry seams creates a 3 dimensional web of moisture impervious barriers, which significantly retards soil moisture movement thus controlling the volumetric instability of the expansive clays.

Ballast pockets are filled with slurry and a seal is created at the ballast formation interface thus preventing future moisture penetration of the clay soil subgrade.

This process can be undertaken without removal and replacement of track infrastructure and equipment is able to rapidly exit and access the track to allow the passage of trains.

1.3 Description and benefits of the lime slurry pressure injection process

1.3.1 Description

The process of slurry injection stabilisation has a history of success in railways dating back to 1968 when it was first used in the USA. A slurry of lime and flyash is pumped under pressure through hollow probes into clay subgrades, filling desiccation cracks, voids, fissures, failure (shear) planes, areas of low compaction and coarse geological formations.

The reaction of lime with clays is well documented, however the incorporation of flyash (a pozzolan) into the slurry enables a cementing action to take place where large voids exist. Where soil structures are devoid of the naturally occurring aluminates and silicates (normally found in clay) that have a pozzolanic (cementing) action with lime, the slurry will "set up". This is because of the catalysing of the pozzolanic reaction in the flyash, by the lime.

The slurry is normally injected to depths of 2 m – 4 m below natural surface, which is known as the seasonal zone of influence. This is the zone over which seasonal wetting and drying of the clay subgrade takes place. Thus shrinking and swelling of moisture sensitive clays occurs in this zone. Below this level moisture contents tend to be stable and hence little or no reactivity is present.

Three probes are simultaneously pushed into the formation between sleepers. The pumping commences when probe tips are approximately 500mm below top of sleeper and the probes continue slowly downward, pumping continuously, radially distributing slurry into the clay formation. At the target depth (lower level of seasonal zone of influence) the probes are stopped and pumping continues to refusal, i.e. when the clay will not accept any more slurry and breakout is observed at the surface. The slurry flow is then turned off and the probes withdrawn. The rig advances two more sleeper spacings and the process recommences.

1.3.2 Benefits

The advantages of using Slurry Injection Stabilisation include:

- Slurry does suppress softening and loss of strength of clay during and following rainfall.
- It significantly reduces swelling in expansive clays.
- It produces a small increase in bearing strength of the clays.
- It is economical for distances greater than 50 m, especially when several small problem areas exist within a locality.
- It can be utilised at depths up to 9 m, which is especially relevant on high embankments.
- No sharp changes in subgrade modulus occur at the interface with untreated sections.
- Can be undertaken between trains and is the least disruptive mode of treatment to train traffic.
- No electrical isolations are needed for treatment down to 2.5 m below top of sleeper.
- Fills ballast pockets and displaces trapped and perched water.
- Controls shear failures by driving out moisture and installing a cementitious seam between the moving surfaces.
- Is effective in stabilising settlement of earth embankments at bridge ends where "dips" commonly occur.
- Is undertaken without the need to remove rails sleepers and ballast.
- Can be undertaken in areas where trackside access does not exist.
- Slurry does not set up hard enough to impede tamping machines.

2 GENERAL DESCRIPTION OF REGION

2.1 Location of clay problem areas

In general, the extent of expansive clays in formations within QR is as listed below:

- Moura Short Line: Annandale - Moura Mine
- Western Line: Toowoomba – Chinchilla
- Great Northern Line: Hughenden – Cloncurry
- Central Line: Kalapa and Aroona flats
- North Coast Line: Archer – Bajool
- Goonyella System: Oaky Ck Branch Line, Peak Downs – Dysart.

2.2 Soil types of the above areas

The soil types in the above areas are mainly black, brown and grey cracking clays. A summary of average grading and Plasticity Index test is given below:

- % Passing 75 micron sieve: 65
- Plasticity Index: 35

These expansive clays generally exist in a plastic state and therefore are susceptible to deformation and volumetric change. In drought and dry seasons these clays reduce their moisture content, which causes shrinkage and surface cracking, but the formation remains stable, as the bearing capacity is adequate. In the wet season the moisture content increases, as water is easily absorbed through the surface cracks. Once these clays become saturated they lose their bearing capacity and have an uneven volumetric increase.

2.3 Climate

Much of these areas of Queensland have a sub-humid and tropical climate. The average annual rainfall varies between 400 mm and 1000 mm with 80 per cent falling between November and April. The wettest month is February and the driest months August and September. The mean maximum temperatures during winter and summer are 20^{0}C for July and 39^{0}C for January.

2.4 Dates of construction

The dates of construction for the formations constructed of expansive clays are listed below:

Line	Construction Date
Moura Short Line	1967
Western Line	1878
Great Northern Line	1908
Central Line	1877
North Coast Line	1903
Goonyella System	1974

The Great Northern Line and the Central Line have had extensive deviation and rebuilding works in the last 40 years, however many of the problems have been in the original formations.

2.5 Construction Practices

Many of the track routes, that are operational today, were constructed by Queensland Rail in the late 1800s and early 1900s. The formations were compacted to no set standard and compaction was left to consolidation over time. It wasn't until the growth of coal mines in the early 1960s that Queensland Rail started to compact its formations, so to comply with compaction tests in accordance Australian Standards (AS.89-1966).

Bulk earthworks were compacted to a density of not less than 95% of its maximum dry density determined by Test 11 of AS.89-1966 (Standard Compaction Method). The material in the top 300 mm was compacted to a density of not less than 100% of its maximum dry density. Batters were constructed as per drawings or as directed by the Superintending Officer but generally embankments were 1 vertical to 1.5 horizontal and cuttings were 1 vertical to 1 horizontal.

In the early 1980s the compaction method was changed to the Modified Compaction Test carried out in accordance with AS1289.E2.1-1977. Bulk earthworks were compacted to a density of not less than 90% of its maximum dry density. The material in the top 600 mm was compacted to a density of not less than 95% of its maximum dry density.

Material for use in the construction of embankments was deemed unsuitable if it included the following:

- Vegetable matter
- Organic clays or silts
- Ashes, coal or the like
- Free draining material susceptible to scouring
- Material which is unstable when wet

Materials suited for the embankment should have a liquid limit not greater than 70% and a plasticity index not greater than 50% and contain a suitable proportion of stone.

Slopes for embankments were as per standard drawings or as directed by the Site Engineer but generally were 1 vertical to 1.5 horizontal.

With the advances in geotechnical understanding of the soils on which track is to be constructed and the sophistication and scale of modern day earthmoving machinery many of the problems being exhibited on the railway lines constructed pre 1980 are significantly reduced or eliminated by the application of sound civil engineering principles.

Substandard materials can be modified by stabilisation. Suitable materials can be imported economically over larger distances due to modern day equipment.

Moisture control during compacting will ensure that target compaction rates are achieved or exceeded. Sub ballast layers of CBR 20 material or better provide a stable platform for ballast and infrastructure, shaped to shed water to a properly constructed cess drain system.

However in areas of highly reactive clays, some degree of loss of track top line and level may be experienced with variations in the seasonal soil moisture cycle, as the natural clay soils are reactive over a 0 m – 4 m horizon.

3 IMPLEMENTATION AND EVALUATION

3.1 Process

The lime flyash slurry is comprised of type F flyash that conforms to Australian Standard (AS) 3582.1, quicklime that conforms to AS1672, and is mixed in the ratio of 2:1 with potable water. In this soil stabilisation treatment, the reaction of the lime flyash with the expansive clay aims at producing an immediate change in soil plasticity, swell, strength and deformation properties in the natural subgrade. The incorporation of Fly Ash, a pozzolan, into the lime slurry enables a cementing action to take place where large voids existed and where natural aluminates and silicates were not present to help stabilise the clay subgrade. This process is called a pozzolanic reaction and is time dependent, thus allowing the soil to strengthen with time.

The percentage of lime [$Ca(OH)_2$] added to the subgrade by slurry pressure injection is determined to be 0.25% of the dry soil weight with a target specific gravity of 1.25 for the mix proportion mentioned above (Stocker, 1996). The diagrammatic process and depth by which the lime flyash slurry is injected into the existing formation without removal of the railway track is shown in Figure 1. (Griffin, 1996)

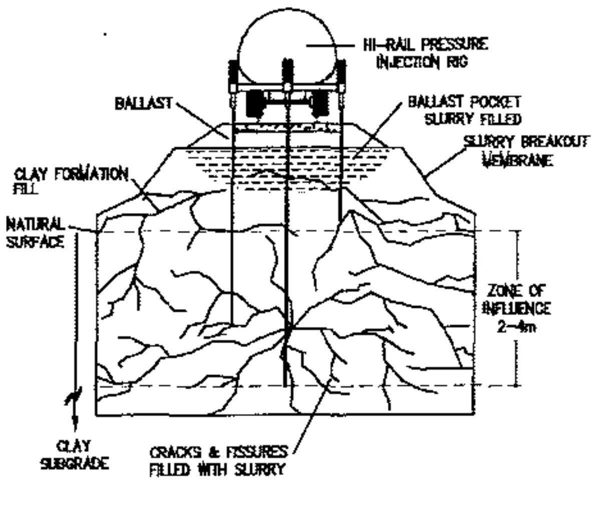

***Figure 1*: Diagrammatic view of pressure injection methodology.**

The Hi-rail injection rig injects in between every second sleeper (1370 mm spacing apart) with three probes. One probe is injected at track centre and the other two at 300 mm outside each rail, to a depth of three metres into the zone of influence.

3.2 Treatment Locations

3.2.1 Moura Short Line Trials

The Moura Short Line trials were outlined in detail in Griffin(1997) and Hogan(1997). This trial evaluated the following formation remediation techniques:

- Reconstruction (Recon)
- Mechanical lime stabilisation (MLS)
- Lime/flyash slurry pressure injection (LSPI)

These formation remediation methods were then compared to control areas, which didn't receive any formation improvement. These techniques were monitored by soil testing, track condition indices and cost effectiveness. Hogan also collected track resurfacing data but this was not included in his report as the publication occurred before all the data became available.

The history of track condition indices is irrelevant unless the history of track resurfacing is also taken into account. This track resurfacing data included the number of occurrences (dips in the track due to formation failure) at locations where techniques were applied over a two-year period (1996/1997). This information is summarised in Figure 2.

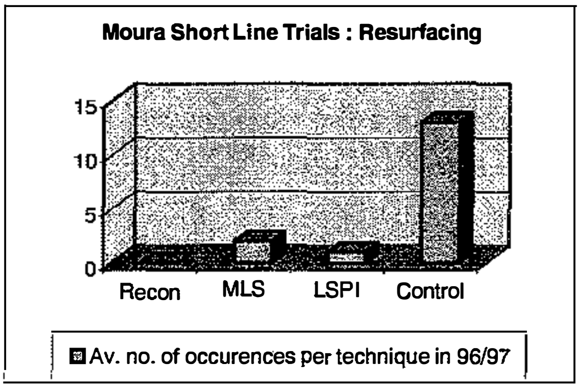

***Figure 2*: Resurfacing data for Moura Short Line trials.**

From the resurfacing data it can be seen that maintenance has been reduced significantly (13x) in the LSPI area compared to the control area. It can be seen that LSPI has stabilised the formation and maintained an adequate bearing capacity by reducing the moisture content variation and the shrink swell component of the soil.

3.2.2 Moura Short Line Upgrade: Gladstone-Moura mine

In 1996, the Moura Short Line was upgraded with a total renewal of rail, sleepers and ballast. As part of this upgrade it was decided to stabilise 27 kilometres of formation in known problem black soil areas using lime/flyash slurry pressure injection. In June 1997, Pavement Technology Ltd was awarded a contract. By October 1999, this contract was completed 3 months ahead of time.

3.2.3 Oaky Creek Branch 21 – 21.5km Goonyella Branch 106.2 – 106.5km, up and down tracks

Lime slurry pressure injection has been used on 37 km of heavy haul coal lines throughout Central Queensland. Much of this work has only been completed recently or in the shadow of track relays, which alters the parameters of rail, sleepers and ballast condition. Therefore it was decided to analyse 1 km on the Goonyella System which was unaffected by the contributing factors of total track improvement. These improvements discount the history of track data.

The formations studied were injected at the request of the Infrastructure Engineer Goonyella System in September 1996 at the following locations shown in Table 1.

LOCATION	Km FROM	Km TO
Braeside	106.205 km Up	106.505 km Up
	106.200 km Dn	106.400 km Dn
Red Mountain	21.000 km	21.500 km

Table 1: Locations of Pressure Injection in Goonyella System.

3.2.4 Rockhampton to Blackwater

The bridge abutments at Bone Creek and Dawson River were injected in 1996 at the request of the Infrastructure Engineer in Rockhampton. The track at these locations had a history of losing top and line that required lifting every 3 months. The Track Section Supervisor at Duaringa has advised in November 1999 that since injection these locations have required minimal lifting. Bone Creek now requires resurfacing every 9 months and the Dawson River every 12 months. This shows that the lime/flyash slurry injection has reduced maintenance costs at these locations.

4 RESULTS

Hogan (1997) showed that general laboratory soil testing such as Shrink/Swell and CBR's displayed minimal improvement in soil that had been injected with lime/flyash slurry. This is understood to be because laboratory testing is done on a micro scale and the mechanisms of the injection process are on a macro scale, affecting a larger matrix. Small-scale laboratory testing, which has been carried out by QR, is not referred to in this paper.

The final result of formation improvement is to achieve an acceptable standard of top and line, with a reduction in resurfacing effort and speed restrictions. Therefore this stabilisation was monitored by evaluating the track resurfacing frequencies and the Track Condition Indices (TCI).

4.1 Track Resurfacing

Resurfacing is a term used to describe the maintenance operation of restoring the surface of a running track to an acceptable condition. A rough running surface can be due to a large variety of track faults occurring either singularly or in combination, e.g. Incorrect cant, centre bound track, low joints, sharp changes in grade, poor line, unstable formation and defective sleepers. These defects do not occur suddenly as the normal process of deterioration of surface is slow unless there is a formation failure. By studying the track resurfacing frequency before and after injection, it can be seen whether there has been an improvement in the formation. This improvement in the formation can minimise speed restrictions and therefore reduce maintenance, train running and operational costs.

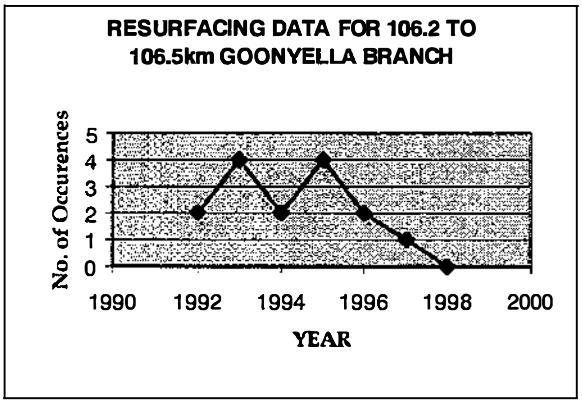

***Figure 3**: Resurfacing Frequency at Braeside Site, Goonyella Branch*

The resurfacing frequency at Braeside over a six-year period (shown in Figure 3) indicates that the resurfacing in 1995 prior to injection was four times a year and in 1997 after injection it is once a year. This has also validated favourable remarks by the local Track Maintenance Co-ordinator who has indicated that no resurfacing has taken place in this area over the last two years (1998 and 1999). This decrease in resurfacing frequency shows that there has been a remarkable improvement in the formation at this location.

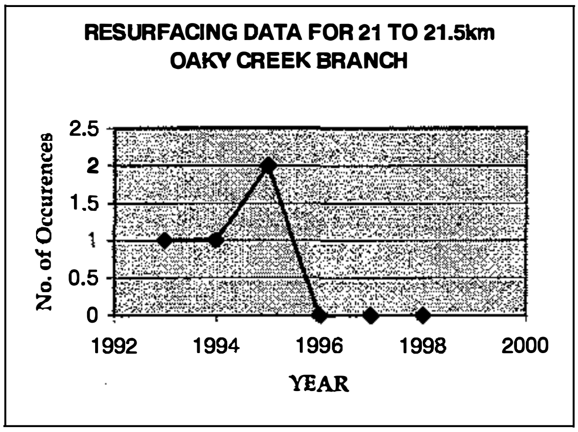

***Figure 4*: Resurfacing Frequency at Red Mountain Site, Oaky Creek Branch.**

The resurfacing at the Red Mountain site over a five-year period (shown in Figure 4) indicates that in 1995 prior to injection, frequency was twice a year and in 1997 after injection was none. This reduction in resurfacing frequency indicates that there has been a significant improvement in the performance of the formation at this location.

4.2 Track Condition Index

The track geometry is recorded and analysed by computerised inspection vehicles. These recording cars measure the following track parameters:

- Twist – rate of change in superelevation in a 3m chord.
- Gauge – a measurement between the left and right rail, 16 mm below the head.
- Versine – variation in horizontal alignment measured centrally in a 10 m chord.
- Top – surface variation measured centrally in a 6 m chord.

From evaluations of this information, Parameter Condition Indices are calculated. The Overall Track Condition Index is the summation of these indices. Therefore QR's track geometry standard is expressed as a TCI. A low TCI is good and a high TCI is poor.

From the TCI data in Figure 5,since injection there has been a slight decrease and levelling off in the condition indices on the Up road at the Braeside site. The reduced resurfacing and the decrease in TCI at this location over the last three years has occurred in a period when axle loads have increased from 22.5 tonne/axle to 26 tonne/axle and the tonnages hauled per year have increased from 45 million gross tonnes per annum to 55 million gross tonnes per annum.

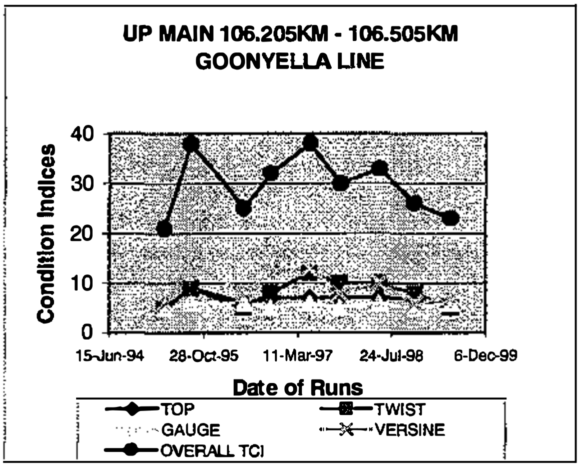

***Figure 5*: Condition Indices on Up Road at Braeside Site.**

The TCI data in Figure 6 shows that the Condition Indices have slightly increased since injection in 1996. Considering there has been no resurfacing over the last two years with record tonnages over this line, it is expected there would be a deterioration of the track. This indicates that the improvement on the Down Road was not as significant as the Up Road but was still successful in stabilising the formation, due to the reduction in resurfacing.

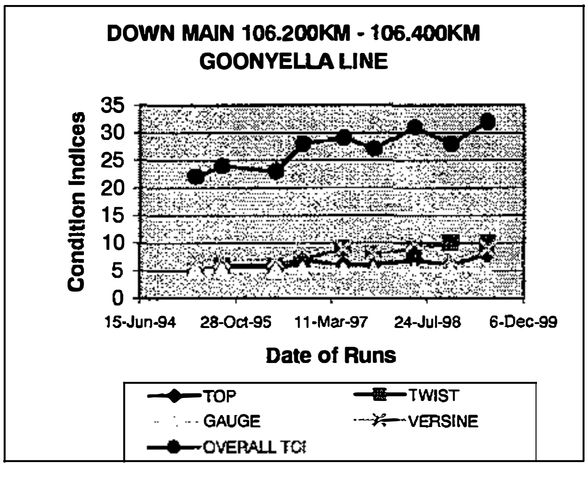

Figure 6*: Condition Indices on Down Road at *Braeside Site.

The Condition Indices have slightly decreased at the Red Mountain site since it was injected in 1996 as shown in Figure 7. As the resurfacing (Figure 4) and the condition indices have reduced at this location, lime/flyash slurry pressure injection has been successful at stabilising the formation.

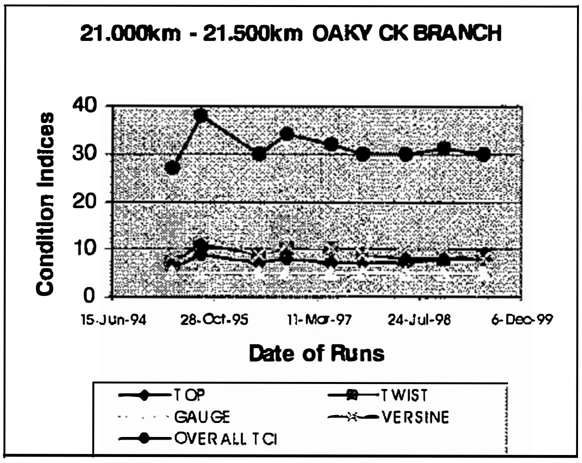

Figure 7: Condition Indices at Red Mountain Site.

5 COSTING BENEFITS FOR FORMATION IMPROVEMENT

These benefits are representative of a costing comparison within the Goonyella System of Queensland Rail. The costing parameters used to determine the cost benefits per kilometre of track are the same as those used by Griffin (1997):

- Train delay costs
- Unplanned maintenance including materials
- Risk of derailment
- Differential maintenance cost

5.1 Cost Parameters

Train delay costs are caused by speed restrictions due to track geometry faults. Considering a 1 km section of track the following statistics apply.

The average speed restriction is 40 km/hr compared to the normal operational speed of 80 km/hr. Therefore 23 trains per day will have lost 17 minutes of running time per track kilometre. An additional 17 minutes lost for train queuing gives a total loss of 34 minutes of scheduled train running. Queensland Rail's liquidated damages for delays to coal trains is $1,500/train/hour therefore each kilometre of speed restriction has a cost of $850/day. Average speed restrictions in the Goonyella System are in force for 30 days per six monthly intervals, thus it can be deduced that the annual cost per kilometre of track for train delays is $51,000.

The unplanned maintenance cost of resurfacing (tamping) track including ballast is $6,000 per kilometre. The frequency for heavy haul routes with poor formation is twice annually. This type of resurfacing only requires minor lifts intermittently. Hence it has been allowed that the total cost of unplanned maintenance per kilometre of track for resurfacing would be $6,000 (2 runs x 1km x 0.5 x $6000/km).

The average cost of $50,000 per annum due to derailments caused by poor formation on the Oaky Creek Branch of the Goonyella System translates to a cost of $330 per kilometre year.

A recent external report showed that the annual maintenance cost for a kilometre of heavy haul track on good formation compared to poor formation or failed geometry is $15,200 per kilometre. Table 2 below summarises the total annual costs (loss of profit) for train delay, unplanned maintenance, derailment and differential maintenance that can be averted by formation improvement techniques.

PARAMETERS	LOSS IN REVENUE ($/yr)
Train Delay Costs	51,000
Unplanned Maintenance	6,000
Derailment Costs	330
Additional Maintenance Costs	15,200
Annual Differential Maintenance & Operational Costs	***72,530***

Table 2: Total Annual Differential Maintenance & Operational Costs.

5.2 Return On Investment

The estimated costs for three different formation improvement techniques are summarised in Table 3.

The following assumptions have been made to estimate the above costs of formation improvement techniques:

- Lime Slurry Pressure Injection (LSPI) can be undertaken between trains without an electrical isolation. 15 kilometres in length can be injected per year.
- Work using the Mechanical Lime Stabilisation (MLS) and Reconstruction (Recon) techniques would require track closures as the cost of temporary earthworks and overhead traction wiring relocation to allow slewing of track could

not be justified. Because of the restriction in operational capacity caused by these techniques only weekly track closures could be justified. Costs for train delays during construction are included in the estimates.

- Mechanical lime stabilisation will require weekly track closures of 8 hrs to stabilise a length of 5 km per year.
- Reconstruction will require weekly track closures of 8 hrs to reconstruct formation for a length of 2.5 km per year.

Formation Improve Technique	Mat. Cost ($)	Mach. Hire Cost ($)	Misc Cost ($)	Total Cost ($)
L.S.P.I.	50,000	75,000	20,000	145,000
M.L.S.	74,000	130,000	150,000	354,000
Recon.	100,000	120,000	300,000	520,000

Table 3: Cost Comparison of Formation Improvement Techniques per Track Kilometre

As in Griffin (1997) the annual differential maintenance and operational costs are assumed to be cumulative and the three formation improvement capital costs are compounded annually at 7.67% (Weighted Average Cost of Capital). From this information the break even point for each technique can be determined and this is represented in Figure 8.

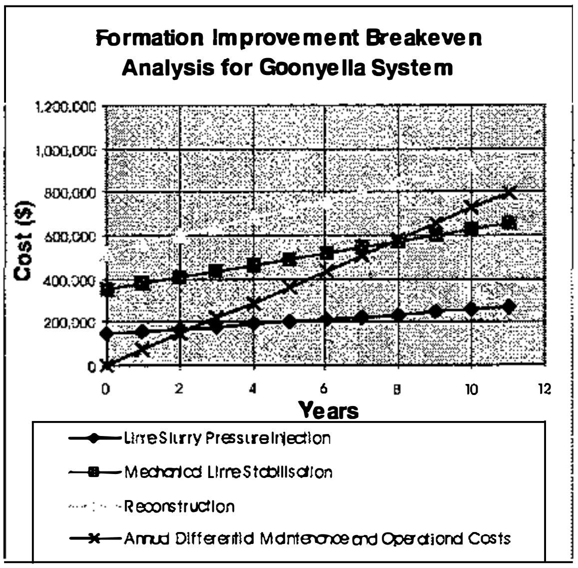

Figure 8: Formation Improvement Break Even Analysis Plot

6 CONCLUSIONS

Overall there has only been a slight variation in condition indices but relatively they have remained the same since pressure injection was completed at the above sites, where no relay or undercutting has occurred. Taking into account the stable condition indices and reduced resurfacing cycles, along with increased axle loads and tonnages hauled, it can be seen that pressure injection has been highly successful at stabilising those existing poor formations.

It can be interpreted from the cost benefit analysis that Lime Slurry Pressure Injection has a break even point of two and a half years which shows that it is a much more economical viable technique than mechanical lime stabilisation or reconstruction. Being able to work on track and under overhead traction wires, pressure injection has a decided advantage over other repair methods. With over 1800 km of expansive clay formations in the QR network, pressure injection stabilisation is being incorporated into our Infrastructure maintenance strategy.

7 RECOMMENDATIONS

Lime/flyash slurry pressure injection does stabilise the moisture content of expansive clay formations but to optimise this process, injection should take place during the dry season. This gives the opportunity for the process to stabilise the formation while moisture content is at its minimum. By filling the cracks with slurry the easy access of water to the sub-surface is minimised. Subgrade squeezes in ballast pockets can be repaired by filling with slurry and displacing trapped water that reduces the bearing capacity of the underlying formation.

It is acknowledged that pressure injection stabilisation is a successful tool in minimising infrastructure maintenance costs within QR.

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