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The Causes of Typical Subgrade Problems in Railway Trackbeds and Mitigation Methods: A Review

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ABSTRACT

Subgrade plays an important role in maintaining satisfactory performance of railway track under repeated traffic loads. In the past, the role of subgrade as the foundation of the tracks, the typical problems affecting it, the causes and corrective measures were not recognized adequately. This study aims at identifying the problems, causes, effects and the remedial measures to correct them. The scope of this study was limited to water-induced railway subgrade problems. Water may cause frost heave, thaw softening, ballast mud pumping, ballast pockets and weakening of the load bearing capacity of a track, resulting in unplanned track maintenance, imposition of speed restrictions, delay, safety issues and damage to third party property. To address these problems, the systematic literature review (SLR) methodology was used in this study, to review some selected published research articles on railway track subgrade problems, causes and solutions. The study found that the typical railway subgrade problems were mainly caused by the presence of excessive moisture content generated from surface water due to rain dew or snow, moisture sucked up by capillary action resulting in increase of moisture in the subgrade or embankment, seepage-water from adjacent area, and lack of adequate drainage. The paper concludes with recommendations that drainage should be provided for railway tracks to reduce the rate of subgrade failures and to improve railway track subgrade functionality, and that good soils, preferably a well-graded material of high-internal friction having high-cohesion without any characteristic of detrimental shrinkage should be used for subgrade.

Keywords. Delay and safety issues, Maintenance costs, Mitigation methods, Railway sub-grade failures, Track geometry deterioration

1. Introduction

Ballasted track has a long history of excellent performance under a variety of loading conditions. It is the most common and, if properly constructed and maintained, the most cost-effective track structure for most railway operations, especially heavy-haul freight operations. The main components of ballasted railway track structures are generally divided into two groups, including superstructure (i.e. the rails, the fastening system and the sleepers) and substructure (i.e. the ballast, the sub-ballast and the subgrade) (Li et al. 2015), as presented in Figure 1. One of the roles of subgrade is to give the ballast and subballast structure a secure foundation. The properties of the subgrade soil determine the amount of loads or stress that can be applied to the subgrade (Loh, 2011). Meanwhile, cohesive soils have been proven to be the most troublesome of all.

Adequate support from the track subgrade is the single most critical element needed for safety and good performance of the track infrastructure. In other words, track subgrade or foundation significantly affects track safety and overall performance, as well as the performance and functions of other track infrastructure components and passing vehicles (Indraratna et al., 2011). Good track support is characterized by good drainage and strong resistance of the ballast, sub-ballast and subgrade layers to excessive deformation and failures under repeated dynamic wheel loads. For problems associated with ballasted track, it is important that track engineers determine the most effective corrective method by identifying the root cause and then prescribing an appropriate remedial action.

In many cases, routine track maintenance activities like ballast tamping and track surfacing do not address the root cause of problems such as excessive track-geometry degradation and mud pumping, ballast pockets, excessive moisture content, they are ineffective as long-term repair methods (Tennakoon et al., 2012, Bruzek et al., 2016).

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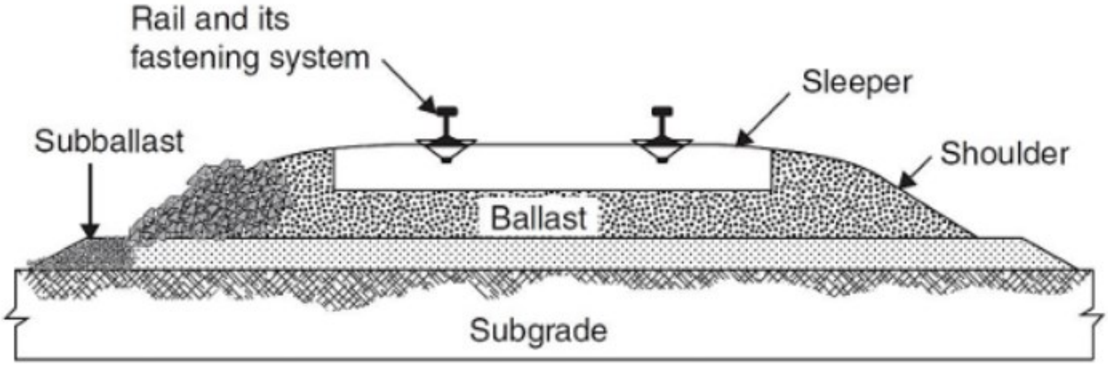

Figure 1: Typical railway track structures, (Indraratna et al., 2011)

Subgrade evaluation and maintenance is both difficult and costly as it depends on several factors which include soil type, moisture content, shear strength, stiffness and consolidation (McHenry and Rose, 2012). Cui et al (2013) observed that the shear strength decreases with the increase of moisture content and hydraulic conductivity decreases with increasing soil suction. Ishikawa et al. (2016) also noted that shear strength decreases significantly due to both water content and fine particles increase.

Toloukian et al., (2018), and Toloukian, (2018), reported that ballast contamination with sand significantly decreased shear strength and lateral strength, causing the ballast layer to fail in providing adequate support to the structure due to the presence of fine particles. Furthermore, poor subgrade and inadequate drainage can cause problems including ballast fouling, ballast pockets and pumping of fine particles. Train speed, cyclic loading, soil fineness, and low-bearing capacity of the formation layer all contribute to subgrade performance. Brough et al. (2003) reported that repeated loading, excess moisture content and poor drainage leads to subgrade failure. Water affects the ballast, sub-ballast and subgrade, but it is the sub-ballast and the subgrade which experience a greater impact compared to the ballast layer (as the latter is a single-sized rock (Ghataora and Rushton, 2012).

The substructure of rail track is primarily focused on the ballast and correction of track geometry, with subgrade invariably a second priority. Selig and Cantrell (2001) reported that the cost of maintenance and deterioration of track components are directly associated with drainage or subgrade conditions. Ghataora and Rushton (2012) observed that the subgrade soil had a major influence on the upper subgrade surface layer, particularly under cyclic loading and in the presence of water. Doung et al. (2013) reported that ballast behaviour significantly depends on subgrade state; in unsaturated conditions, the ballast and sub-soil interface did not change but, in a near saturated state, a significant number of fine particles migrated into the ballast. Brough et al. (2006) also noted that the overall track stiffness depends on the subgrade, thus the deterioration of vertical track geometry.

Progressive shear failure occurs due to overstressing of clay subgrade, an event which can be avoided by placing granular material to enhance drainage. Wenty (2005) reported that particle attrition resulted in the development of slurry at the ballast subgrade interface due to the presence of water and heavy dynamic loading. Overloading the subgrade creates water -pockets which cause attrition and can be avoided through the use of granular blanket.

Sharpe and Caddick (2006) reported that sand-blanketing prevents upward movement of the slurry by filling the voids within the subgrade. If slurry is formed under the clay it is retained in the clay and, in due time, it dries out

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with the sand blanket increasing the stiffness of the granular layer. Sand blanketing is a common method of protecting subgrade soil and is generally a permeable layer of fine granular material thereby allowing water to drain from the subgrade surface. However, in wet condition, the track becomes vulnerable - a situation which impacts on each component of the rail track system, in particular, the subgrade soil (Bonnet, 2005).

Rail network construction plays a significant role in national economic and social development. In the past two decades or so, especially in countries with rapidly developing economies, the escalating growth in vehicle numbers and weights means that railway tracks may have operated beyond their original design capacity. The main problem associated with railway track beds is excess water infiltration into the structure, this phenomenon seriously accelerates structural failure since the foundation's soil is sensitive to water. Damage may originate from excess water due to (e.g.) impeded subgrade drainage, inadequate compaction, moisture-sensitive materials and lengthy drainage pathways, thus, the strength, modulus and related mechanical properties of the subgrade may rapidly degrade in the presence of excess water.

Even worse, under repeated traffic loading, track distress may develop more rapidly, owing to the interaction between excess subsurface water and the challenging stress conditions induced by the loading. Excess resilient deformation may occur, representing the subgrade's recoverable deformation under traffic loading. The accumulation of large plastic strains may then be experienced by the subgrade carrying the railway tracks. Consequently, this endangers the long-term performance and serviceability of the track substructure under repeated traffic loading.

This paper provides a review of research activities done on railway subgrade problems. The scope of this study was limited to water-induced railway subgrade problems, such as: ballast mud pumping and its effects on track performance, effects and remediation of subgrade attrition with mud pumping, effects and remediation of ballast pockets, progressive shear failure, excessive plastic deformation, and excessive moisture content. These distresses could lead to loss of track geometry, reduced ballast strength/ stiffness; and consequently, lead to track failure.

1.1 Aim and Objectives

This study focused on typical subgrade problems in railway track-beds. Since the railway foundation or subgrade is usually subjected to stress and environmental actions, identifying the effects of these typical problems and the corrective measures are very important. Thus, this study aims to identify the typical subgrade problems in railways and the management of the distresses, in order to extend the track life and improve service reliability. The train mass transit system is one of the most important modes of transportation, and a critical component of the economic development of a nation. Besides, the railway plays a key role in reducing emissions and mitigating global warming.

The specific objectives of the study are outlined as follows:

i) To identify the typical subgrade problems, causes and the characteristics of railway subgrade, by a critical review.

ii) To evaluate the effects and response of railway track-beds to the typical problems, by a critical review.

iii) To identify the corrective measures to the typical problems affecting the performance of subgrade in railway track-beds, by a critical review.

2. Methodology

The methodology of this study consists of four steps:

(i) General research,

(ii) Inclusion/exclusion criteria,

(iii) Data research, and

(iv) Selection of the most relevant papers.

2.1 General search

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The landscape is predominantly flat, exhibiting a gentle incline towards the north and northeast with a gradient of approximately 1:960 (Odemerho and Ejemeyovwi, 2007), where the elevation remains below 20 meters above sea level. Key characteristics of the region include the shallow depth of aquifers, with the water table fluctuating between 0 to 4 meters, a generally flat terrain, substantial annual rainfall, and soils that are highly permeable. These factors result in minimal runoff at the site and suggest that the majority of rainfall is retained within the soil. This improves the decomposition processes carried out by bacteria and fungi, as well as facilitates the leaching of pollutants into the aquifer (Olobaniyi and Owoyemi, 2006).

2.1.1. Hydrogeology of the study area

These practices directly endanger the shallow aquifers within the study area and pose significant risks to human health overall. It is widely acknowledged that pollutants resulting from human activities—whether from non-point sources or dispersed point sources—can ultimately infiltrate groundwater, leading to its contamination.

2.2.Methods and materials

2.2.1. Laboratory analysis

Upon collection, the samples were stored in polypropylene beakers for subsequent analysis. Prior to the field sampling procedure, the beakers and containers designated for sample collection underwent thorough cleaning and were soaked in distilled water, which had been acidified with 1.0 ml of $HNO3$, for a duration of three (3) days. A systematic approach led to the collection of 10 water samples from diverse water sources throughout the nation.

The systemic literature review (SLR) methodology began by searching for published articles on railway subgrade problems, the causes, effects and remedial treatments, from the works of numerous researchers. This effort threw up many published articles on the above subject matter.

2.2. Inclusion/exclusion criteria

In searching for and obtaining research articles for this study. Google scholar and google search engine to search for relevant papers were relied upon (Silvius & Schipper, 2014b). The recommendation that "researchers should consult Google Scholar especially for a relatively recent article, author or subject area" (Bauer & Bakkalbasi, 2005), were followed. In this study, articles published in the last 23 years were consulted and a total of 83 articles from all the downloaded articles, after screening some articles out, were used for this study. Our key search strings where the phases 'railway track subgrade problems', 'subgrade failures', 'causes of railway failures ', effects of railway subgrade failures', 'railway subgrade remedial treatments. Since subgrade failures can seriously affect the rail structure and directly endanger traffic safety (Wang et al., 2014), articles published in peer-reviewed journals, books, book chapters, dissertations, and conference proceedings, regardless of their impact factor were considered.

2.3. Data search

The literature search retrieved a total of 136 articles. Following the removal of 30 duplicates, the remaining 106 articles were screened based on their titles and abstracts, resulting in the further removal of 23 non-relevant articles. Subsequently 83 articles were used for this study. To achieve these reductions, the search was focused on a specific area of interest.

2.4. Selection of the most relevant papers

To reduce the size of the database in the previous steps and to review a reasonable number of studies, the search was reduced specifically to railway subgrade problems caused by water infiltration. This step aims to identify the most relevant studies to focus on and eliminate irrelevant studies. During the selection phase, searches were conducted on the causes and corrective measures of typical railway subgrade problems due to excessive

Table 1. Inclusion and exclusion criteria used to select papers

Empty Cell	Criteria	Justification
Inclusion	Papers published between 2000 and 2023.	To focus on the relevant publications, not older than 23 years.
	Publications in peer-reviewed journals, conference papers.	To concentrate on high-quality articles and other documents for a broader and more comprehensive litera-
	Papers focused on railway subgrade failures.	The emphasis on work related to subgrade failures in railway transportation.
	Empirical and experimental studies on causes and solutions to railway subgrade failures.	To include research on railway subgrade only.
Exclusion	Papers focusing only on subgrade failures.	The purpose of the research is to review the existing literature on railway subgrade failures, causes and solu-
	Studies in a language other than English.	The researchers involved in this project can read English language only.

3. Results

From the findings of the review of available investigation reports on water-induced subgrade problems in railways, the following combination of common/leading causes of subgrade problems in railways and mitigating measures are hereby presented and discussed:

3.1. Progressive Shear Failure

According to Bhat and Thomas (2015), progressive shear failure, also known as general subgrade failure, is the shear failure of the subgrade caused by the progressive upward and sideways pressing out of the top part of the subgrade (where the stresses are highest) due to repetitive traffic loading (Figure 2). The plastic movement of the soil brought on by excessive tension at the subgrade surface from repetitive loading is known as progressive shear failure. The route of least resistance is gradually followed by the subgrade soil as it squeezes upward and outward.

3.1.1 Causes of progressive shear failure

The stress path gradually approaches the failure envelope with increasing loading cycles, which leads to sudden and unacceptable deformation in the subgrade as the mean effective stress decreases due to the accumulation of excess pore pressure (Li and Selig, 2005). This situation primarily arises when the drainage in the subgrade is poor, leading to the accumulation of excess pore pressures due to sustained cyclic shear stresses (Ansal and Erken, 2000). In soils of relatively high permeability (e.g. gravels and

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and sands), fully drained conditions can be expected with insignificant excess pore pressures, while in low-permeability soils with high fines content, considerable increase in excess pore pressure occurs under undrained conditions (Powrie et al., 2019).

Fine-grained soils, especially those with significant clay content, are the main source of this issue. Due to forming and the formation of increased pore water pressure from repeated loading, these soils lose strength and become softer as their moisture content rises (Powrie et al., 2019).

3.1.2 Mitigation methods of progressive shear failure

Mamou et al. (2018) study showed that increasing the clay content from 7 % to 14 % in a saturated sand-clay mixture could reduce excess pore pressures and increase the cyclic shear stress threshold. However, increasing the clay content to 24 % and beyond resulted in an increase in excess pore pressure with insignificant effect on the cyclic shear stress threshold.

Ballast is added underneath the ties to counteract the depression in the track substructure that is mirrored at the surface. Subgrade stability is often improved when more ballast is added since it increases the depth of the ballast and decreases soil tension at the subgrade level. Water is trapped in the depression, though, and this tends to negate the potential improvement. Therefore, the stability issue brought on by the progressive shear failure cannot be resolved by simply adding more ballast without also adjusting the deformed subgrade surface layout to facilitate drainage (Powrie et al., 2019). A matching depression beneath the track corresponds to the heave of material at the track side, as seen in Figure 2.

3.2. Excessive plastic deformation ·

According to Cai et al. (2018), though the subgrade experiences progressive shear deformation in tandem with progressive shear failure, severe plastic deformation is categorized as a distinct subgrade problem type. It encompasses both the vertical deformation brought on by progressive compaction and consolidation of subgrade soils under repeated traffic loads as well as the vertical component of progressive shear deformation. The subgrade develops cumulative plastic deformation as a result of repetitive loads. Under normal circumstances, the plastic deformation caused by a single axle load is practically insignificant.

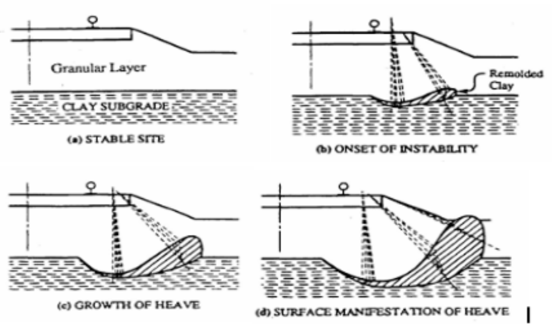

Figure 2: Progressive shear failure development (Adopted from Bhat & Thomas, 2015).

However, with repeated load applications, the subgrade's plastic deformation may build up to such a large extent that it might negatively impact the track's operation.

Furthermore, plastic deformation typically develops unevenly along and across the track. Therefore, severe plastic deformation may result in a change in track geometry that is inappropriate. Excessive plastic deformation develops more quickly in cohesive soil subgrades with water access and in recently built subgrades (Cai et al., 2018).

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3.2.1 Causes of excessive plastic deformation

(i) The subgrade remains stable but cyclic loading leads to unfavourable track settlement due to undrained shear deformation or volumetric strain (Arulrajah et al., 2005); equilibrium is eventually reached as the excess pore water pressure stabilises. Although consolidation and creep settlements contribute to track settlements under static loading, it is widely accepted that cyclic loading can accelerate plastic deformation (Arulrajah et al., 2005, Cai et al., 2018). Thus, plastic settlements induced by cyclic loading were assessed under different stress states and load combinations, as well as capturing varying soil properties. For example, the role of stress state considering the initial confining pressure and stress anisotropy was investigated by Leng et al. (2017) and Tong et al. (2022).

The development of cumulative plastic deformation in the subgrade is a function of the repeated loading (Lackenby et al., 2007). The plastic deformation produced by a single axle load is essentially negligible under normal conditions. However, the plastic deformation in the subgrade may accumulate to such a significant level with repeated load applications that it can severely affect the performance of the track. Moreover, the development of plastic deformation is usually non-uniform along and across the track. Hence, excessive plastic deformation can lead to unacceptable track geometry change (Indraratna et al., 2015).

The development of excessive plastic deformation is more rapid for a newly constructed subgrade and for a cohesive soil subgrade with access to water (Wang et al., 2022). In the latter case, with the same mechanism as that for the progressive shear failure, when a depression at the subgrade surface occurs, it collects water, causing an increased softening of the subgrade near the depression. With repeated loading the clay squeezes out and the underlying clay in tum softens; thus, the depression deepens and the ridges of soft subgrade material collect around the pocket, which forms a larger water-filled pocket (Brough et al., 2003).

Other studies have demonstrated the influence of loading frequency (i.e. representing the train speed) on the accumulated strain based on triaxial test results (Truong et al., 2021, Wang and Zhang, 2021, Silva et al., 2023). Initial water content and compaction quality were also reported as decisive factors contributing to significant plastic deformation of soft subgrade soil (Leng et al., 2017).

Furthermore, results obtained from cyclic triaxial and hollow cylindrical testing shows that moving load and corresponding principal stress rotation can generate increased plastic settlement (Graube and Clayton, 2014, Xia et al., 2014). For instance, Grabe and Clayton (2009) suggested that the rate of increase in plastic strain resulting from the principal stress rotation was inversely proportional to the clay content of the subgrade (clay contents varying from 7 to 24 %).

3.2.2 Mitigation methods of excessive plastic deformation

(i) To offset the loss of track elevation caused by the excessive plastic deformation in the subgrade, more ballast material generally must be added to the track, which results in an increased depth of ballast material. When

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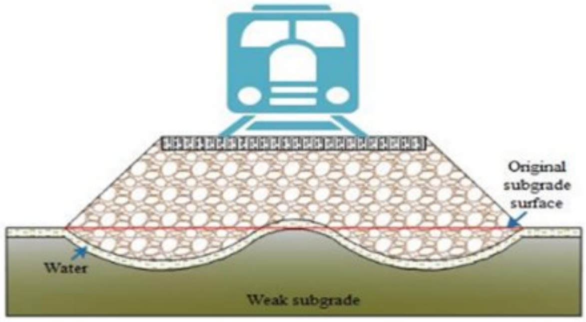

Figure 3: Excessive plastic deformation (ballast pocket) in track subgrade (Cai et al., 2018).

ballast continues to replace the subgrade soil and as it is repeatedly added under the sleepers, a severe manifestation of accumulated subgrade plastic deformation, termed ballast pocket, can form. Although adding more ballast increases the ballast depth, this cannot completely solve the problem of excessive plastic deformation development since the ballast pocket traps water, which in tum leads to softening of the subgrade soils. Furthermore, the ballast may become contaminated with the subgrade soil particles, thereby degrading the characteristics of the ballast or the granular material (Powrie et al., 2019).

3.3. Ballast Pockets

Ballast pocket is a depression as the subgrade surface gathers water, leading to a greater softening of the subgrade close to the depression. This mechanism is the same as that for progressive shear failure. The clay squeezes out and the underlying layer softens with repeated loading; as a result, the depression deepens and ridges of soft subgrade material gather around the pocket, creating a bigger pocket in the ballast that is filled with water. Ballast pockets are a common subgrade problem that often results in higher track-geometry degradation; therefore requiring more track maintenance (Li et al., 2015). The effect of ballast pockets is that it often traps water within the pocket, commonly referred to as the ”bathtub effect”, which keeps the subgrade material at the ballast-subgrade interface at a high moisture level. This leads to significantly lower soil strength than the same material in a dry condition. Ballast pockets and associated poor drainage were identified as the root causes for a revenue service track that experienced chronic and significant track -geometry degradation (Bayse and Li, 2015a, Bayse and Li, 2015b).

3.3.1 Causes of mud pumping

Some causes of ballast pockets are:

(i) Ballast pockets are usually caused by a soft subgrade that gradually deforms laterally and vertically. During track repair, new ballast is frequently added to restore the track alignment. Over time, the ballast addition may also transform into a ballast pocket, thus, the cycle continues. The process, therefore, increases cost of maintenance, it is not sustainable, and it also pollutes the The "bathtub effect," which occurs when water is trapped in ballast pockets, causes the subgrade to continuously have high moisture content, when compared with the same material in a dry state, resulting in decreased soil strength Dash and Majee (2021).

3.3.2 Mitigation Methods of ballast pockets

Some of the mitigation methods for ballast pockets:

(i) New ballast is added during track maintenance to restore track geometry elevations. Though, increasing the ballast depth does not entirely address the issue of severe plastic deformation development since the ballast pocket retains water, which eventually causes the subgrade soils to become softer Bayse and Li. (2015b). This cycle can develop into a ballast pocket over time. Increased ballast material must typically be added to the track, resulting in a deeper layer of ballast material, to compensate for the loss of track elevation brought on by the excessive plastic deformation in the subgrade. A serious form of accumulated subgrade plastic deformation known as a "ballast pocket" may develop if ballast keeps replacing the subgrade soil and is put beneath the ties (Li et al., 2015). Examples of ballast pockets across and down the track are

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shown in Figure 4).

(ii) Stabilizing the upper ballast layer using a geogrid at the upper embankment, to improve stress distribution and reduce the stress on the subgrade. The geogrid forms a soil mat foundation as it goes into a tensional state and it engages with the ballast. The geogrid should be placed immediately below the tamping zone depth, but as high in the section as possible in order to mitigate ballast movement. The 13 ft, 1.5 in wide triaxial type geogrid was installed on top of the subballast after the track was removed and the subballast graded to -12 in from the final bottom of tie elevation. Since the ties are 8.5 ft long, the geogrid was symmetrically exposed for about 27 inches or so on each side of the ties. The track was placed on new concrete standoff blocks for rough height adjustment and then new ballast dumped around them prior to tamping and alignment (Bayse and Li, 2015a).

(iii) The use of ballast drains is a common practice to remediate ballast pockets. Although they cannot drain the entire individual ballast pockets (since ballast pockets form an uneven or undulating subsurface interface), they provide a general improvement in the bearing capacity and shear resistance of the soil matrix (Bayse and Li, 2015b). Instaling ballast drains at the bottom of the low ballast pocket regions were to allow excess water to drain thereby drying the subgrade and increasing its strength. As shown in Fig. 4, ballast drains are relatively quick, inexpensive and easy to install. Several years following the installation, water continued to seep out from the ballast drains installed (Dash and Majee, 2021).

3.4. Ballast Mud Pumping

Mud pumping is divided into ballast mud pumping and subgrade mud pumping. Ballast mud pumping means that when the ballast is dirtied, mud is squeezed or pumped out under the dynamic load of train, while Subgrade mud pumping means that subgrade soil or weathered rock is eroded and softened by water, therefore resulting in liquefaction into mud so as to be squeezed and pumped under the dynamic load of train, which causes permanent deformation of the subgrade (Burns et al. 2006).

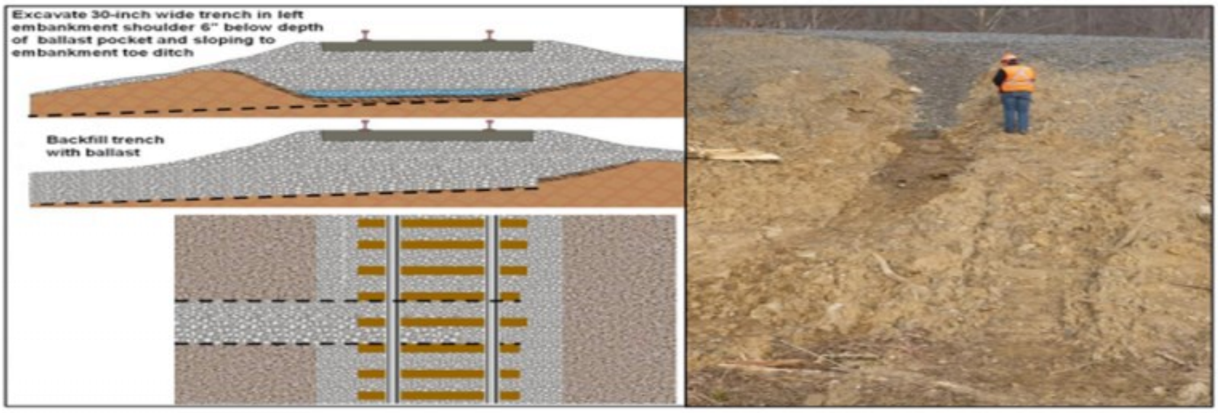

Figure 4: Ballast drain installed to improve drainage in ballast pocket (1 inch = 2.54 cm) (Bayse and Li, 2015a).

Image 1: Geogrid placement and track restoration (Xiaoqiang and Jiankun, 2019).

Subgrade mud pumping mainly involves the migration of fine soft subgrade particles into the coarser layer (Singh et al., 2019) while ballast mud pumping is the dust or other fine substances accumulated inside the ballast aggregate (Nguyen et al., 2019) (Figures 6 and 7).

The development of ballast mud pumping, will eventually lead to subgrade mud pumping, because once the ballast is polluted and crashed into powder, it will lead to poor permeability causing the track bed to harden, where water will be easily accumulated in the center of subgrade resulting in foundation or subgrade mud pumping (Yang, 2002).

3.4.1 Causes of mud ballast pumping

Studies generally believe that mud pumping of subgrade is the fine ingredients in soil transit with water (Imadi and David, 2006, Panich and Nair, 2003). Sufficient conditions for occurrence of the mud pumping are:

(i) Abundant fine ingredient in embankment soils;

(ii) Fine sand is missing in ballast with the existing channels of mud pumping;

(iii) Existing Free water;

(iv) Existing recycling load.

When a train passes, due to the action of impact load, railway sleeper is pressed down, and the excessive pore water pressure increases as well; after the train has passed, railway sleeper suddenly restores to its normal position, which leads to the pumping of fine-grained soil in the bed and thus the forming mud pumping phenomenon (Alobaidi and Hoarse, 2006a, Alobaidi and Hoarse, 2006b). In short, the disadvantageous effect combination of soil, water and dynamic load is the cause of mud pumping generation in subgrade beds.

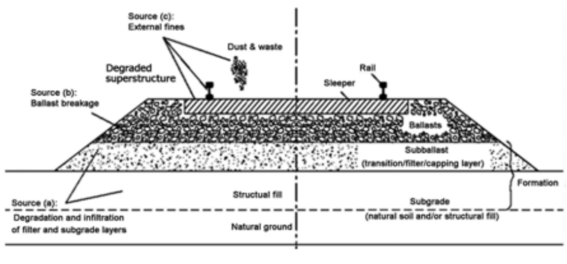

Figure 5: The sources of mud pumping generation (Nguyen, 2019).

Figure 6: Ballast Mud Pumping (Burns et al., 2006)

Figure 7: Ballast mud pumping with standing water (Wilk et al., 2019)

3.5 Subgrade Mud Pumping

Three elements trigger the subgrade degradation, i.e., soil plasticity, water, and dynamic loads. Soil and water can be classified as internal parameter while the dynamic train loading is the external factor in forming the subgrade mud pumping. The beginning of development of mud pumping process is due to the existing soft saturated subgrade soil subjected to repetitive loading (Singh et al., 2019), and due to subsequent passage of trains over the wet spots, the cyclic loading leads to the penetration of the ballast, which forced the fines to squeeze into the coarser upper layers and foul the void ballast.

At unloading state as the sleeper restores to normal position, the suction force generated, cause the migration of subgrade fine particles. The suction effect depends heavily on the ties-ballast distance as the gap increases, the pumping fine will actively move (Sussman et al., 2017, Yu et al. 2016).

As pore water pressure development is the main influence on the dissipation of fine-grained particle of subgrade soil which causes the occurrence of mud pumping (Duong et al., 2014). High intensity of water content in subgrade soil surface enables the rapid rate of pore water pressure diffusion provoked by suction force through loading and unloading

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process. Basically, mud pumping will appear only in moving train operation as under the repeated load, the subgrade soil will produce plastic deformation thus causing deformation and destruction of the subgrade soil (Cai et al., 2015). The major factor such as depth, speed train and loading influence the generation of excess pore water pressure in soil when under train loading (Kettil et al., 2008, Li et al., 2012).

Other than interpenetration between ballast and subgrade layer, the pore pressure is another contributor to mud pumping occurrence. The development of pore water pressure in the subsoil causes the migration of fine particle into ballast void as stated (Duong et al., 2014). Cyclic loading is the main reason for the increment of pore water pressure in railway formation which exaggerates the infiltration of subgrade fines through the surface layer (Nguyen et al., 2019).

On the other hand, the presence of water supports the generation of pore-water pressure when under external loading thus allowing dissipation of this pressure to bring fine particles up to the ballast layer (Li et al., 2012).

Furthermore, drainage condition plays a key role in subgrade degradation-induced mud pumping; it is obvious, mud pumping cannot occur without a certain condition of high-water table under the track. Numerous site investigation findings show that mud pumping occurs more frequently during high rainfall periods due to rising water tables and the increase in surface water concentration in the surface area (McDowell et al., 2005).

Drainage issue can influence the instability and shear failure of the railway foundation (Sussman et al., 2012, Hudson et al., 2016, Li, 2018) as poor drainage tends to associate with water ponded or trapped beneath the track, accelerating the degradation rate of track structure. For example, Duong et al. (2013) found that fines rise upwards more rapidly at a near saturated state with a high-water content (e.g., > 14%), and this does not occur in unsaturated conditions.

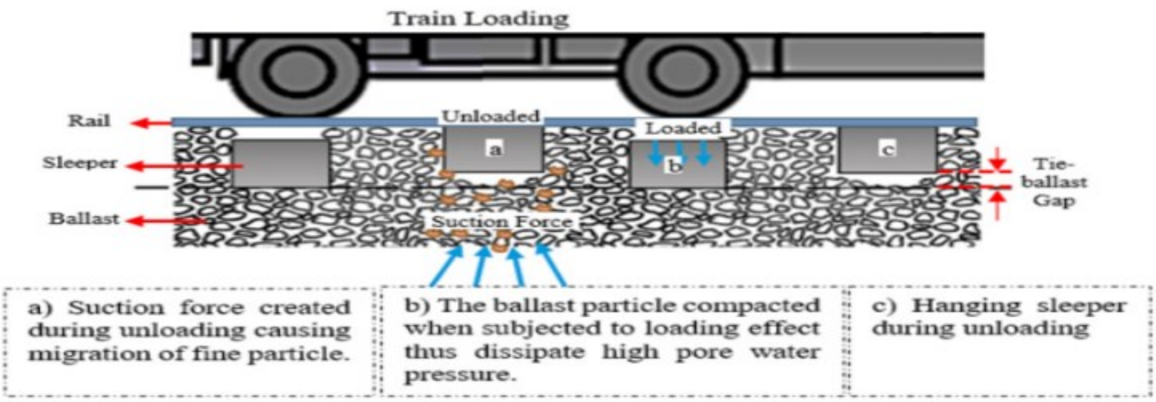

Figure 8: A schematic diagram of migration of fine particle grained through pumping effect (Duong et al., 2014).

Figure 9: Subgrade mud pumping

Figure 10: Fine materials migrating upwards

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3.5.1. Causes and effects of subgrade mud pumping

(i) When water is present, the attrition by-products and water mix to create mud. This mud pumps upward into the ballast voids when loading is applied repeatedly. The procedure will result in track settling and a reduction in the ballast's drainage capacity, which ultimately lowers the ballast layer's resilience and shear resistance. Typically, silt and clay particles make up the mud in the ballast. This attrition has been seen in cuts with soft subgrades and silt stone, shale, slate, or even sandstone subgrades that have durability issues under repetitive loads (Wilk et al., 2019).

(ii) Mud in ballast can also be created by particles arriving from the surface or by the breakdown products of ballast or sub-ballast. Efforts must be made to determine the reasons for the mud since the repair process for these issues is considerably different from the repair associated with subgrade attrition. (Wang et al., 2014).

(iii) Subgrade mud pumping is mostly caused by an unfavorable mix of soil, water, and dynamic load. According to (Tzanakakis, 2013), load factor, soil factor, and environmental factor (soil temperature and moisture) are the three main causes that may lead to the emergence of subgrade issues. However, these elements working together frequently result in subgrade issues (Bhat & Thomas, 2015).

(iv) Tzanzkakis, (2013) reported that soft track is caused by weak subgrade, which includes clay, silt, saturated or wet soils, and progressive shear failure. An overstressed subgrade can also result in poor resistance to train loading, too high or steep embankment pockets, progressive shear failure (and the accumulation of ballast pockets), and inadequate thickness of the top formation and ballast.

3.5.2. Mitigation methods of mud pumping

(i) In Dash and Majee work in 2021, the researchers concluded that by mechanically shielding the subgrade from attrition and penetration by the coarse-grained ballast on top, a layer of appropriately graded sub-ballast, can be placed to prevent mud pumping from the subgrade and prevent the formation of slurry. Additionally, because of the sub-ballast's filtering qualities, it stops slurry from migrating upward at the sub-ballast-subgrade interface.

(ii) Enough drainage is necessary to prevent water from staying in the ballast and at the ballast-subgrade interface, which will lessen the mud pumping issue. Other subgrade issues can result in costly track repair or track subgrade failures (Liu et al., 2013).

(iii) Based on field investigations, fines particles were observed to be pumped up from the degraded shale subgrade due to water weakening. Draining excess water or installing a barrier layer would address the underlying mechanisms producing the subgrade mud pumping because the saturated conditions cause the shale to break up into fine particles and pump upward. Though due to the difficulty of draining the excess water, barrier methods were selected using geosynthetic materials

(Wilk et al., 2019).

(iv) Traditional methods for improving soft ground include excavation and replacement, preloading, vertical drains, sand or sand-lime piles, stone columns, lime or lime cement stabilization, etc. They will be costly and time-consuming (Bhat & Thomas, 2015). Thus, the application of geosynthetics frequently provides a more straightforward, economical, and ecologically friendly solution to the issue. Additionally, according to (Bhat & Thomas, 2015), geosynthetics can carry out the following tasks:

- Separation of the sub-ballast and/or other granular material from the subgrade
- Act as a filter between the subgrade and the granular material placed over the subgrade
- Reinforce the formation and increase its strength and stiffness. Subgrade improvement through stabilization techniques has also been proven to be effective.

No one solution has been found to address every subgrade issue, but as water is a factor in the majority of these failure modes, drainage enhancement is nearly always included in the solution (Tzanakakis, 2013). Shoulder cleaning or ballast undercutting may be the best option in particular circumstances. However, it is crucial to remember that ballast undercutting and shoulder cleaning also increase track drainage. Making the ballast thicker is another popular corrective measure. This choice is temporary because it results in the creation of ballast pockets, which ultimately leads to another failure (Tzanakakis, 2013).

3.6. Excessive Moisture Content in Subgrade Bed

High moisture content in soils is well-known to compromise soil's bearing capacity, particularly after heavy rainfall or during spring thaw events. This vulnerability to high moisture conditions can, in turn, have a detrimental impact on the performance of pavements, particularly during the spring season when soil moisture levels are at their peak. Furthermore, volumetric changes in soils, such as swelling in expansive soils or frost heaves, are often the result of excess moisture (Guo et al., 2016, Wang et al., 2016).

Problems most likely occur in old sections of the track that do not meet the current requirements and design criteria. However, water-related issues can also appear on high- speed tracks in cold areas (Trinh et al., 2012). Determining the properties of ballast, sub-ballast layers, and subsoil to distinguish the reasons for weak track geometry stability is usually necessary (Brough et al., 2003). The relationship between track geometry problems and the water content of track substructure layers is complex. Many studies and laboratory tests have shown that a track is usually vulnerable to geometry deterioration even long after flooding (Hasnayn et al., 2017). According to Ghataora and Rushton (2012), it can take over four days for water to dry from a single- track section but up to 10 days from a double-track section drained at one side. (Wang et al. 2017) observed in their ground penetrating radar (GPR) studies that high water content has been detected more in transitional structures than in line sections. This usually causes problems, because the dynamic forces are increased in transition zones (Sanudo et al., 2016). Consequently, Wang et al. (2017) proposed that drainages in transition structures should be more effective than in line sections. High water content can also reduce the resonance frequency of the ground and cause vibration issues when train speeds increase (Jiang et al., 2015).

3.6.1 Causes of excessive moisture content

The causes mainly include:

(i) Cyclic loading and fine-grained materials with excessive water content are bad combination with regard to track geometry stability (Li and Selig, 2005). The effects of excessive water content appear either as an

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increased need for maintenance or, in flooding situations, even as derailments or significant damages (Hasnayn et al., 2015). Even a small increase in water content can cause a significant decrease in loading resistance (Ferreira and Teixeira, 2011), and severe drainage issues can lead to landslides (Duong et al., 2013).

(ii) Insufficient drainage leads to the excessive moisture content in the subgrade, caused by blockages in the transverse or longitudinal drainage channels, preventing surface water from draining quickly and resulting in water infiltration into the subgrade; (Hachem and Zornberg, 2019).

(iii) The presence of a higher proportion of fine particles in the fill material within the subgrade area results in higher moisture content compared to areas with coarse-grained soil, as fine grained soil has a higher water-holding capacity (Duong et al., 2014).

3.6.2 Mitigation methods of excessive moisture content

(i) The wicking geotextile properties facilitate the accelerated drainage of pavement subgrades and granular layers. Wang et al. (2017) developed a laboratory-based physical model to understand the effectiveness of the wicking geotextile on pavement infrastructure. They concluded that wicking fibers could wick out moisture even when the water content was close to the optimum point. Furthermore, the wicking fibers helped to rapidly reduce the moisture content of the soil after rainfall to initial moisture percent. This draining action increases the stiffness and load-carrying capacity of the pavement, while also mitigating the unstable volume changes in the soil resulting from moisture variations. The unique cross-section of the filaments within the wicking yarn, coupled with suitable surface chemistry that makes the material hydrophilic (water loving), creates a suction potential through capillary action. This suction potential encourages moisture to move from the soil to the wicking filaments, increasing drainage capability (Zornberg et al., 2017).

(ii) Excessive moisture content in the subgrade can be reduced by replacing ballast and subballast with clean materials and installing two geotextiles: MIRAFI RS580i reinforcing geotextile and MIRAFI H2Ri wicking geotextile to address drainage and moisture issues. The combined geotextile not only promotes the drainage of pavement subgrade soils but also serves as a medium for redistribution of excess moisture without sacrificing pavement capacity De Alvarenga, CBS, (2021). In high plasticity soils, where moisture fluctuation can have a significant impact on soil's behavior, the geotextile aids in redistributing moisture to minimize the risk for localized failures due to swelling and shrinkage (expansive soils are sensitive to changes in moisture content, with even a minor increase of 1 to 2% leading to severe swelling) (Zamin et al., 2021). This redistribution also contributes to the pavement's overall resilience, preventing localized areas of subgrade weakness that could lead to pavement structural issues. In addition, this combined geotextile plays an important role of preserving the integrity and quality of granular base material by serving as a filter media that prevents the contamination of the granular base with fines from subgrade soil. Using this type of geotextile supports potential life cycle cost savings, the high quality of granular base materials is preserved, and the subsequent maintenance and rehabilitation can be limited to the surface layers of the pavement (Guo et al., 2019).

(iii) As with other high-strength geotextiles, the combined geotextile provides mechanical

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stabilization to the pavement's subgrade and in turn helps improve the load bearing capacity of a pavement structure. The mechanical stabilization action of geotextile is realized through redistribution of traffic-induced stresses on top of the subgrade, which reduces the accumulation of permanent deformation (Biswas et al., 2021a). Further, it provides lateral restraint and minimizes the potential for lateral shear flow of aggregates in the ballast and sub-ballast layers. This further contributes to reinforcing the subgrades's structural integrity and its service life (Puppala et al., 2023).

4. Conclusions

This paper analyzed the causes and mitigation measures of typical subgrade in railways, such as subgrade mud pumping, ballast mud pumping, progressive shear failure, excessive plastic deformation, ballast pockets, and excessive moisture content in the subgrade bed. The following conclusions were drawn:

(i) Progressive shear failure, also known as general subgrade failure, is the shear failure of the subgrade caused by the progressive upward and sideways pressing out of the top part of the subgrade (where the stresses are highest) due to repetitive traffic loading. Progressive shear failure is formed when the stress path gradually approaches the failure envelope with increasing loading cycles, which leads to sudden and unacceptable deformation in the subgrade as the mean effective stress decreases due to the accumulation of excess pore pressure. This situation primarily arises when the drainage in the subgrade is poor, leading to the accumulation of excess pore pressures due to sustained cyclic shear stresses. To mitigate this failure, ballast is added underneath the sleepers to counteract the depression in the track substructure that is mirrored at the surface. Subgrade stability is often improved when more ballast is added since it increases the depth of the ballast and decreases soil tension at the subgrade level.

(ii) The subgrade develops cumulative plastic deformation as a result of repetitive loads. Under normal circumstances, the plastic deformation caused by a single axle load is practically insignificant. However, with repeated load applications, the subgrade's plastic deformation may build up to such a large extent that it might negatively impact the track's operation. To offset the loss of track elevation caused by the excessive plastic deformation in the subgrade, more ballast material generally must be added to the track, which results in an increased depth of ballast material.

(iii) Ballast pocket is a depression that occurs when the subgrade surface gathers water, leading to a greater softening of the subgrade close to the depression. Ballast pockets are usually caused by a soft subgrade that gradually deforms laterally and vertically. This mechanism is the same as that for progressive shear failure. Ballast pockets are a common subgrade problem that often results in higher track-geometry degradation; therefore requiring more track maintenance. New ballast is added during track maintenance to restore track geometry elevations. Though, increasing the ballast depth does not entirely address the issue of severe plastic deformation development since the ballast pocket retains water, which eventually causes the subgrade soils to become softer. This cycle can develop into a ballast pocket again over time. Stabilizing the upper ballast layer using a geogrid at the upper embankment, to improve stress distribution and reduce the stress onto the subgrade is a preferred method of mitigating this particular subgrade problem.

(iv) Mud pumping is divided into the types: ballast mud pumping and subgrade mud pumping. Ballast mud pumping means that when the ballast is dirtied, mud is pumped out under the dynamic load of train, while Subgrade mud pumping means that subgrade soil or weathered rock is eroded and softened by water, therefore resulting in liquefaction into mud so as to be squeezed and pumped out under the dynamic load of train, which causes permanent deformation of the subgrade. One way of mitigating this problem is to provide enough drainage, in order to prevent water from staying in the ballast and at the ballast-subgrade interface, which will lessen the mud pumping issue. Draining excess water or installing a barrier layer would address the underlying mechanisms producing the subgrade mud pumping because the saturated conditions cause the shale to break up into fine particles and pumped upward. Though, due to the difficulty of draining the excess water, barrier methods perform better by using geosynthetics.

(v) Excessive moisture content in soils is well known to compromise soil's bearing capacity, particularly after heavy rainfall or during spring thaw events. This vulnerability to high moisture conditions can, in turn, have a detrimental impact on the performance of pavements, particularly during the spring season when soil moisture levels are at their peak. Furthermore, volumetric changes in soils, such as swelling in expansive soils or frost heaves, are often the result of excess moisture. Cyclic loading and fine-grained materials with excessive water content can affect track geometry stability. The presence of a higher proportion of fine particles in the fill material within the subgrade area results in higher moisture content compared to areas with coarse-grained soil, as fine grained soil has a higher water-holding capacity. Insufficient drainage leads to the excessive moisture content in the subgrade, caused by blockages in the transverse or longitudinal drainage channels, preventing surface water from draining quickly and resulting in water infiltration into the subgrade. The application of a geotextile made up of MIRAFI RS580i reinforcing geotextile and MIRAFI H2Ri wicking geotextile not only promotes the drainage of pavement subgrade soils but also serves as a medium for redistribution of excess moisture without sacrificing pavement capacity. In high plasticity soils, where moisture fluctuation can have a significant impact on the behavior of soils, the combined MIRAFI RS580i reinforcing geotextile and H2Ri geotextiles aids in redistributing moisture to minimize the risk for localized failures due to the swelling and shrinkage of expansive soils. This redistribution also contributes to the pavement's overall resilience, preventing localized areas of subgrade weakness that could lead to pavement structural issues. In addition to moisture storage potential, H2Ri geotextiles plays an important role of preserving the integrity and quality of granular base material by serving as a filter media that prevents the contamination of the granular base with fines from subgrade soil. This supports potential life cycle cost savings when MIRAFI RS580i and H2Ri geotextile is used, as the high quality of granular base materials is preserved, and the subsequent maintenance and rehabilitation can be limited to the surface layers of the pavement.

The findings of this study can guide the correction of deficiencies in the typical subgrade problems in railways. This is of significant importance to ensure the efficiency, safe, cost effective and reliability of operating the railways. Additionally, it serves as an important reference for the subsequent operation and maintenance of railway track beds. The appearance of track geometric problems is typically a good sign of track subgrade failures. Therefore, new, cutting-edge testing techniques designed to detect railway subgrade failures should be made available always, in order to accurately assess the amount of track subgrade failures, before it becomes difficult and more expensive to correct.

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