CESARE'17
COORDINATING ENGINEERING FOR SUSTAINABILITY AND RESILIENCE
Dead Sea, Amman, Jordan
3-8 May 2017
JORDAN UNIVERSITY OF SCIENCE & TECHNOLOGY
IRBID - JORDAN

INFLUENCES OF SLEEPER/CROSSTIE MATERIAL CHOICES ON GEORISKS IN RAILWAY SYSTEMS UNDER CLIMATE UNCERTAINTIES

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Keywords: Resilience, Robustness, Stability, Georisks, Sleepers, Materials, Railway, Infrastructure, Climate Change, Uncertainties.

Abstract. *Railways have been a critical catalyst for economic and social growth around the world. They have been developed using local materials to effectively suit whole-life design, construction and maintenance. The choice of construction materials often affect the life cycle performance and play a key role in resilience of rail assets and infrastructure in an uncertain setting derived from geotechnical risks, operational changes, natural hazards and climate change effects. Nowadays, in railway industry, various materials are being installed in railway tracks as supporting structure. Railway sleepers or ties are an important element, which redistributes wheel load onto track foundation and importantly secures rail gauge. Among them is manufactured by steel, timber, polymer, composite and concrete. The choice of these sleeper materials is mainly arose from local suitability and compatibility in a specific railway network. This research is the world first to investigate the georisks and potential consequences on track capacity and performance of railway systems under climate uncertainties. It highlights track failure modes, short-term and long-term stability, and ground-borne vibration, which causes excessive maintenance and service downtime. The insight into the influence of sleeper material choice will help saving life cycle costs and reducing carbon footprint from repetitive track reconstruction activities.*

1 INTRODUCTION

Railways are a key transportation system to many countries around the world. Maintaining its design geometry over their operational life and a continuous service, with minimal interruptions to maintenance is a challenge to railway engineering and extremely necessary to guarantee safety and economic efficiency [1-3]. Throughout the world, a railway track supported by ballast is widely accepted for conventional railway lines due to its advantages as inexpensive implementation costs and easy maintenance [4-6]. Ballasted railroad track infrastructure is a layered system essentially comprised of two main parts: superstructure and substructure as shown in Figure 1. The superstructure includes the main load-supporting elements of the track; it is basically constituted of rails, the fastening systems, sleepers and ballast. The substructure is related with the geotechnical system comprising the sub-ballast and subgrade or formation [7]. The interaction between the components once they experience the loads imposed by the passage of trains is what determines the successful, reliable and safe operation of ballasted railway tracks [8].

Sleepers perform crucial roles in railway track system. Their major function is to transfer and distribute the loads applied on the rail seat to the ballast, sub-ballast and subgrade layers on an appropriate pressure level [9]. Additionally, sleepers are responsible for assuring lateral resistance to the rails and stability of gauge width between the rails [7]. They also should attenuate vibrations caused by the passage of trains, acting as an intermediary elastic layer between rails and the ballast bed [10]. This interface of interaction between sleepers and the ballast bed is determinant both for the superstructure as for the substructure behaviour and stability. The ballast condition under the sleeper influence the bending moments which the sleepers are submitted as well as the load path, once they are dependent on the contact area between sleeper and ballast particles [11-12]. Moreover, sleeper's characteristics as size, dimensions, shape, weight and material also affect this contact area exerting influence mainly in the track lateral resistance, but also on pressure distribution [12].

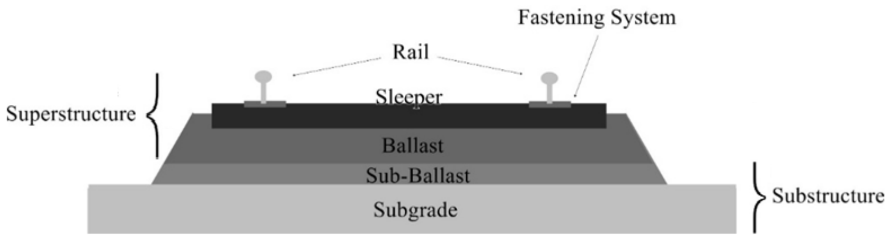

Figure 1 Schematic Track Structure

Research directed to the understanding of the geotechnical behaviour of railway lines still represent a small part of all efforts made to improve the knowledge of the railway track system [6]. In smaller number are the works that relate the sleepers to the geotechnical behaviour, especially those that emphasize the type of sleeper employed. This present paper has as major purpose elaborate an overall review about each principal sleeper type based on literature review, analyse their behaviour and how this is reflected in particular geotechnical risks, resulting in a comparative study.

2 TYPE OF RAILWAY SLEEPERS

Since the beginning of the history of railways, timber is the main and most used material for sleepers. Due to a scarcity of noble wood, the high price and increased maintenance requirements, the need for other materials has raised [13]. Concrete and steel have emerged as options to new lines. Mechanical advantages and lower susceptibility to wear are the major appealing features presented by steel and concrete sleepers. However, they do not have mechanical properties compatible with the timber sleeper, making ineffective the replacement and co-operation. Therefore new timber sleepers still are a more favourable option in a short term to replace the damaged sleepers in existing lines [14]. More recently, environmental concerns and the search for an alternative able to reproduce behaviour more comparable to timber have increased the research on plastic/polymer and fibre composite sleepers [14].

2.1 Timber

A major advantage of timber sleepers is their flexibility, which results in a great ability to resist vibrations deriving from dynamic loads in railway track system [15-16]. The ease of handling, replacement, and adaptation to track systems are other benefits of this material. Accordantly to Manalo [17], timber sleepers can be suited to all types of railway track. Additionally, the electrical isolation provided by timber sleeper is valuable to the signalling system and only plastic or fibre composites sleepers could also match this characteristic. Esveld [7] arranged timber sleepers into two categories: softwood (e.g. pinewood) and hardwood (e.g. beech, oak, tropical tree). Hardwood timber is the most common sleeper material in railway lines through the world. Its advantages over the softwood timber are its greatest strength and durability [7]. However, over the years the hardwood timber has become increasingly expensive, its availability is reducing and which is still available no longer has the same quality [17].

Although more resistant to fungal decay, softwood sleepers offer less resistance to end splitting, gauge spreading, and spike hole enlargement than hardwood sleepers. Furthermore, they are less effective in transmitting loads to the ballast section as hardwood sleepers. Due to this difference in loads transmission hardwood sleepers and softwood sleepers should not be used together on the railway track [18]. Due to diverse environmental conditions, woods are susceptible to severe degradation due to the attack of various organisms. The resistance of untreated wood to fungal decay in service above ground is low, affecting its durability. Non-durable timbers generally require preservative treatment if they are to be used in exposed conditions, adding significantly to their cost. Moreover, there is growing concern regarding the use and disposal of this impregnated material their consequences for the environment [13].

2.2 Concrete

After the Second World War, the use of concrete sleepers had a significant increase in Britain and Europe due to the timber scarcity. Progressively, reinforced and pre-stressed concrete sleepers have replaced timber and steel sleepers [12] due to their prolonged life cycle and reduced maintenance costs [16]. Two varieties of concrete sleepers are offered in the market accordingly to Esveld [7]: reinforced twin-block and prestressed monoblock sleepers. The twin-block consists of two blocks of reinforced concrete connected by a steel bar or stiff steel beam. While monoblock sleepers consist of one prestressing reinforced concrete beam [19]. Monoblock concrete sleeper is the type that has greater acceptance in the market due to its superior durability in the face of unfavourable environments. Another advantage observed is the resistance to twist, failure commonly presented by twin block concrete sleepers. Because of this usual failure the installing process of this type of sleeper requires greater care, making it more difficult to handle and contributing to a lower acceptance, even with their reduced weight compared to monoblock sleepers.

Concrete is known for its high resistance to compression, on the other hand, presents weakness when it comes to tension. Due to this characteristic, monoblock concrete sleepers use the technique of prestressing to withstand the dynamic loads arising from the passage of the train. This procedure consists of the tensioning of steel rods before or after the concrete is moulded. Prestressed concrete presents increased ductility, higher flexural strength and resistance to cracking [18]. The stability and slight position movement offered by prestressed concrete sleepers because of its heavy weight meant that it had a significant acceptance in high-speed lines. At the same time, the great weight reduces mobility, making it difficult to transport and being necessary specific equipment for installation which increases the costs of concrete sleepers. One of the causes of this high weight is a need for greater thicknesses in comparison to timber sleepers with the aim of reducing dynamic tension at the bottom fibre [20].

Costs for producing and maintaining prestressed concrete sleepers are considerably elevated. Their initial costs are about twice that the hardwood timber sleepers [16]. However, due to its high durability and specifications that comply with the solicitations of a railway system, prestressed concrete sleepers can be currently considered as the best cost-benefit to serve ballasted railway lines [20] and the preferred sleeper to railway tracks nowadays [8].

2.3 Steel

With a typical lifecycle of about 50 years, steel sleepers emerged as a first option to substitute timber sleepers around the 1880s [16]. A steel sleeper presents higher mechanical strength, can be lighter than timber and are easy to handle, they can even be operated manually. However, their use is usually limited to lightly traveled tracks [22]. An excellent gauge restrains and increased lateral resistance due to its geometry are other technical advantages presented by steel sleeper. Additionally, damaged sleepers also have commercial value [7], since the steel can be recycled several times and reused in the railway industry [22].

In the search for further improving the characteristics of steel sleepers, the traditional orthogonal sleepers have been replaced by Y-steel-sleepers (Figure 2). The development of this new model provided a further reduction in weight of steel sleepers and gain of resistance against cross movements due to the amount of accumulated ballast in its central part as a consequence of its design similar to the letter Y [23].

Figure 2 Y-Steel-Sleeper [23]

A significant disadvantage of steel sleepers is the due to the difficulty to achieve a reasonable packing with ballast, requiring special care during the installation process and tamping [16]. Other problems as fear of corrosion, fatigue cracking in the fastening holes caused by moving trains, high electrical conductivity (that can lead to problems with track circuit signalling) and excessive noise also contribute to the inferior popularity of steel sleepers [17]. However, the greatest restriction of the use of steel as a material for the production of sleepers is its excessive value [12].

2.3 Plastic, Polymer and Composites

Material scarcity, as well as environmental concern, motivates researchers regarding new materials capable of satisfying the railway system requirements. Develop a structure that is economically competitive and meets the needs of the industry is a major challenge of civil engineering. There is a constant search for a material that is durable, reasonably easy to produce and maintain, have attractive costs and meets the expected requests effectively. [17]. A key concern in the railway industry is the replacement of damaged and deteriorated sleepers in existing tracks [16]. The importance of the development of the polymer and composite sleepers is due to the capacity to design it to mimic the timber behaviour, which cannot be achieved with concrete and steel sleepers. A factor of extreme importance for the maintenance of timber tracks [17]. Moreover, polymer and composite sleepers require low to almost no maintenance, thus this improved life-cycle makes them a suitable alternative for areas that are harder to maintain such as tunnels, bridges, and turnouts. Another advantage is its sustainable approach, what makes them be notable in the face of the constant increase of concern over the existing environment in the current industry [17].

Many studies are given in the area of polymers and composites as material for the manufacture of sleepers. A composite material is manufactured from two or more distinct materials combined to achieve characteristics not found in those who compose [24]. There are several efforts towards improve the characteristics of the materials already used in the railway track engineering (wood, steel and concrete) as applied to the polymer by itself or composite polymers, using mainly fibres [17]. A fibre composites system characteristically consists of a lightweight polymer matrix with strong fibres inserted into it [17]. The fibre reinforcement sustains the load due to its high strength and can be applied as reinforcement only in the longitudinal direction or longitudinal and transverse directions.

Accordantly with Manalo [17], fibre composites could be perfectly suitable for the production of railway sleepers. These composite can be engineered based on the required structural applications and manufactured with almost the same dimensions and weight to that of hardwood timber. Additionally, fibre composites railway sleepers offer high strength, are light and presents a longer lifecycle, reducing maintenance costs. Moreover, fibre composites are easy to handle, they can be drilled in situ for the connection of the fastener system and inserted under the track as timber sleepers. Another appeal of polymer and composites sleepers is the environmental question. There are many efforts in study polymers produced from recycled plastic. Since 1990 several U.S. companies and institutions has shown interest in the production of sleepers from recycled plastic. According to Lampo [25], the recycled plastic material can help reduce emissions of greenhouse gas, save millions of trees, reduce chemical contamination due to the preservatives present in timber sleepers and also adding commercial value to a large amount of waste. Economically most fibre composite sleeper developments still have disadvantages compared to traditional sleeper materials due to higher initial costs [24]. Companies as Carbonloc Pty Ltd, University of Southern Queensland (USQ) in Toowoomba, Australia, has devoted researchers regarding the shape optimization of polymer sleepers based on the load and support pattern and reducing considerably the volume of polymer needed while assure that it still achieve all the proprieties needed to cope with the railway solicitations [17].

3 CARBON FOOTPRINT

The construction industry is one of the greatest consumers of raw material and energy, as well as a major generator of environmental pollution [26]. Consequently, the choice of materials is a subject of ongoing debate. Considering railway engineering, several concerns arise when discussing manufacture, preservative treatment and disposal of damaged and deteriorated sleepers. The manufacturing process of railway sleeper can be associated with substantial environmental impacts. Resource required to the production of sleepers as energy and material are responsible for a large greenhouse gas emission [27]. Materials such as concrete and steel consume a significant amount of energy during production and could dispense respectively 10-200 times more carbon dioxide into the atmosphere than hardwood timber sleepers [17]. Moreover, gases are also generated during the transportation and installation of sleepers and a great quantity of waste is resulted, mostly from the harvesting of timber [27]. However, during the service life, the decay of timber sleepers continues resulting in impacts to the environment. This is due to the fact that during their growth, trees keeps in its structure carbon that is absorbed from the atmosphere and once timber has been cropped it progressively liberates carbon dioxide back to the environment. Then this emission is extending even after the disposal of these sleepers until the end of its decomposition. As a comparison parameter, Crawford [27] founds that emissions related to the service life of timber sleepers can be up to six times greater than the emissions associated with reinforced concrete sleepers. Another concern related to using and discarding of timber sleepers comes from the practice of chemically impregnating them with creosote to preserves it from biological deterioration [24]. Despite being widely used, toxic substances are present in these chemical preservatives which do not easily decompose in nature and are volatiles [26]. So they are gradually released into the air during the life cycle of the sleeper may cause environmental pollution and present risks to human health. On the other hand, plastic sleeper, when made from recycled plastic, can be beneficial to the environment. Its production not only saves the use of other materials but also provides functionality to a considerable amount of waste as well as attaching commercial value to a material that would be discarded [25]. Though, the use of non-recycled plastic for manufacturing sleepers generates concerns mainly because of some plastics being a by-product of oil in addition to being non-biodegradable. Furthermore, the service life of the sleepers has a great impact on its sustainability since it determines the demand of material over the years, and also the amount of discarded units, which generates great impact especially on the use of land. The expected service lives of the different types of sleepers are listed on the Table 1.

Table 1 Expected Life Cycle of Different Types of Sleepers

Material	Service Life (years)	Material	Service Life (years)
Timber	15-25 [17]	Steel	20-30 [17]
Concrete	50 [17]	Plastic/Polymer	over 50 [14]

4 CLIMATE UNCERTAINTIES

The fifth assessment report of the Intergovernmental Panel on Climate Change [28] summarized the trend of the climate change. The IPCC pointed out that warming of climate system is obvious and definite. The IPCC summarized that the temperature increased from 0.0045°C per decade in the past 150 years to 0.074°C per decade in the past 100 years, and 0.177°C per decade in the past 25 years, which shows acceleration trend. As a result, atmosphere and ocean are warming, polar ice caps are melting and extreme events will be more likely and frequently to take place. Figure 3 shows similar trend through plotting the data from IPCC.

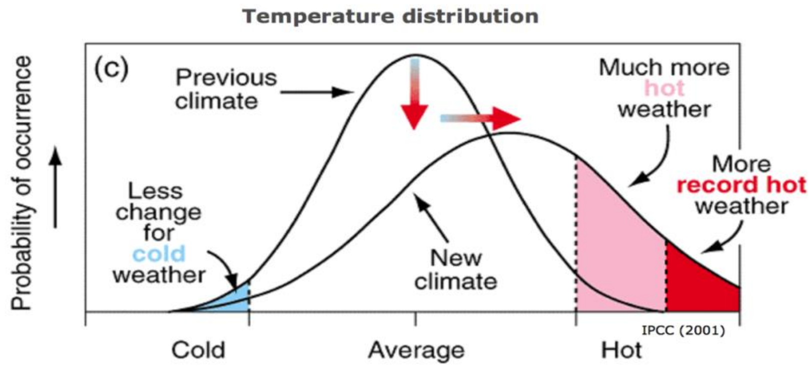

Figure 3 Temperature change between previous years and recent years

According to Figure 3, the occurrence of extreme cold weather will take place less due to global warming. At the same time, there is much risk of hot weather in the tails of the distribution and events of more extreme hot weather happen frequently. In this case, it can be conducted that more hot weather will bring much drier, and warmer winter also can be more humid. In addition, there is significant increase in the CO_2 concentrations in the atmosphere. CO_2 concentration also indicated the increase trend from 280 parts per million in 1750 to 380 parts per million in 2005 [28] The fifth assessment report of the Intergovernmental Panel on Climate change [28] showed an impact from recent climate-related extremes, such as heat waves, droughts, floods, cyclones and other extreme events. The IPCC also suggest that some frequency of combinations with extreme weather patterns will increase. For instance, the frequency of intensity of heavy rain in summer will increase, which means high temperature combined severe rain will appear together and as consequence the combined effect of these extreme weather will be more serious rather than effect of individual climate change on track superstructures and substructures.

5 GEORISKS

Railway track substructure is expected to resist the static and dynamic loads that are generated by the passage of moving trains. Additionally, the cyclic characteristic of these loads has a great influence on the track long-term behaviour. A major challenge when it comes to investigating the behaviour of the substructure arises due to the variability of the substructure component's proprieties. Attributable to this characteristic, the analysis of dynamic and repeated loading becomes more demanding due to the non-linear stiffness presented by granular materials [5].Understand how the substructure components react when subjected to these loads, how the loads are transferred from the sleeper to the track substructure and how the interaction between the components of the superstructure and substructure occurs is extremely important to the design, efficient operation and security of railway roads. Table 2 illustrates georisks under climate uncertainties.

Table 2 Georisks of rail infrastructure due to sleeper materials

Climate Impact Group	Risks	Safety Impact	Performance Impact	Likely Negative Impact from Climate Change	Long or Short Term	Influence of sleepers
Sea Level Rise	Increased flooding generally	High	High	High	Long	• Regarding the design of the track bed, the load distribution pattern at the sleeper/ballast interface is a parameter of critical importance since it is a major function of the sleeper smoothly distributes the loads imposed on it by rails to the subsequent layers. • The formation is often damaged by excessive moisture content especially when flooding occurs after rains. Concrete sleepers tend to cause formation failure quicker than other sleepers because they are often used in a heavier operation, resulting in a higher bearing pressure. Therefore, if formation is undermined by water, it is highly likely that such track will fail even though it looks perfect from the top view. • Reconstruction of track formation and foundation is required if damage occurs.
Increased Rainfall	Settlement	Medium	High	Low	Long	Need to monitor the ground movement and the relationship with rainfall intensity. Settlement under heavy haul track is usually accelerating higher. However, deteriorated timber sleepers by moisture content can lose the vertical stiffness and yield excessive deformation and higher total settlement.
Increased Rainfall	Stability	High	High	High	Long	Embankment, rock cutting, earth cuttings and culverts are at risk of being instable, disregarding of any type of sleepers.
Heat	Track buckling	High	High	High	Long	Sleepers have the major role of providing satisfactory lateral resistance to avoid lateral movements of rails. If the lateral forces overcome the lateral resistance of sleepers, rail buckling may occur. In fact, timber and steel sleepers perform poorly laterally under elevated temperature.

Table 2 Georisks of rail infrastructure due to sleeper materials (cont'd)

Climate Impact Group	Risks	Safety Impact	Performance Impact	Likely Negative Impact from Climate Change	Long or Short Term	Influence of sleepers
Increased Rainfall	Geotechnical Failure	Medium	High	High	Long	• Cyclic stresses are a major concern for the stability of the subgrade. Repeated traffic overloads are related with many subgrade problems, being the progressive shear failure and excessive plastic deformation some of the causes of formation failure most commonly found in railways around the world. Furthermore, the overstress can wear the superficial soil of the subgrade that combined with water form mud. More than the weakening of the soil, this mud under repeated loads can pumps into the ballast and damage the drainage of the track (using any type of sleepers). Fine-grained soils, as clays, are usually more susceptible to these failures modes. • Timber sleepers are often decayed with high moisture content. • Steel sleepers can be oxidized at higher level.
Cold snap	Damage	Medium	High	Medium	Short	• Steel, plastic and resin in composite sleepers become very brittle in very low temperature. These sleepers could be damaged by ice-stiffened tracks, resulting in excessive groundborne noise and vibration. • Freeze-thaw effects can cause concrete sleeper damage. • Ice-stiffening can cause ballast dilation, cracking subballast, cracking formation, and frozen rail joints. • Icing can also cause frozen rubber/under sleeper pad / under ballast mat.

6 CONCLUSION

Despite the importance of the sleeper/ballast interaction to the whole stability of the track, few studies are available focused on this interface. From the bibliographic review in this work, it was possible to observe the influence of the type of sleeper in the interaction between this and the substructure of the railway line. Load transition pattern, sleeper capacity to dampen dynamic loads and bear lateral movements are important aspects to the stability of the track substructure. Lower stiffness materials as some polymers, composites, and timber offer a better packing with the ballast so the contact pattern becomes more uniform and less concentrated stresses are transferred to the ballast particles and formation. Therefore, diminishing the imminence of geotechnical failure and also increasing the durability of the ballast layer. Moreover, vibrations are better absorbed reducing one generator of ballast wear and risk of damage to surrounding structures due to ground vibrations. Lateral stability is highly influenced by piece geometry. Therefore, sleepers with unusual formats such as twin block concrete sleepers and Y-shape steel sleepers has some advantage over more conventional ones. Concerning the material, the weight and surface of concrete guarantee this type of sleeper excellent resistance to lateral movements. Moreover, the deficiency of concrete sleepers under dynamic loading action can be mitigated with the use of under sleeper pads. For a future perspective, polymers and composite sleepers could bring enormous advantages to the railway industry. They require less maintenance and have longer expected service life. Usually, plastic sleeper has a powerful environmental appeal because it can be made from recycled material as well as can be recycled after disposal. Furthermore, polymers tend to be a less aggressive material to the substructure. Its properties can be able to reduce the effects of dynamic loads. Thus, the track geometry may be maintained for longer periods.

ACKNOWLEDGEMENT

The first author wishes to thank the Australian Academy of Science and Japan Society for the Promotion of Sciences for his Invitation Research Fellowship (Long term) at the Railway Technical Research Institute and The University of Tokyo, Tokyo Japan. The second author would like to thank Brazil's Sciences without Borders for her scholarship at the University of Birmingham. The authors wish to gratefully acknowledge the financial support from European Commission for H2020-MSCA-RISE Project No. 691135 "RISEN: Rail Infrastructure Systems Engineering Network," which enables a global research network that tackles the considerable challenge in railway infrastructure resilience and advanced sensing under extreme events (www.risen2rail.eu).

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