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Assessment of access materials to reduce soil stress on construction sites

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Assessment methodologies and mitigation measures for the impacts of road projects on soils – ROADSOIL

D3.3 Assessment of access materials to reduce soil stress on construction sites

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Executive summary

Soil compaction negatively affects physical, chemical and biological processes and can enhance other soil threats, such as soil water erosion and the loss of soil organic matter. The risk of soil compaction is particularly present during infrastructural construction activities, mainly because these activities involve the use of heavy machines, vehicles and equipment for transport or hauling of materials on natural and cultivated soils. The long-lasting effects of soil compaction and low recovery rates make compaction a major threat to soil health. It follows that prevention of soil compaction is vital for securing soil functions.

This report summarizes a field experiment that was set-up to investigate the effects of different access materials on soil stress for tyre- and tracked motorised machines and vehicles used in construction activities. Three types of access materials were included: composite mats (DURA-BASE® Advanced Composite Mat System™, Newpark Mats & Integrated Services), sand track and wooden mattresses. Experimental traffic was performed by two motorised machines with a metal-track undercarriage system, a 16-tonnes bulldozer and 21-tonnes excavator, and by two vehicles equipped with tyres, a 11+29-tonnes tractor-trailer combination and a 40-tonnes lorry. Bolling probes were used for quantification of mean normal soil stress during traffic at 0.20 and at 0.40 m depth from the soil surface.

Access material affects stress propagation with depth differently. The difference may be explained by differences in thickness of the access material and by differences in the elasticity or stiffness of a material, which affects the stress transmission through the material. Differences between stress at 0.20 and 0.40 m depth was generally larger for Composite mats than for Wooden mattresses and the Sand track.

Mean normal soil stress was affected by using access materials, although more so for the wheels with tyres than for the tracks: the tractor’s rear axle and trailer and, in particular, the lorry had the greatest reductions of soil stress. For the tracked machines, the dozer and excavator, the use of access materials reduced mean normal soil stress at 0.20 m depth, but not at 0.40 m depth. Moreover, the level of stress under the tracked vehicles was generally low. This is explained by the low mean ground pressure, due the large contact areas of the tracks.

The composite mats and sand track reduced soil stress better than the wooden mattresses. Taking into consideration the thickness and weight per running metre of the composite mats, sand track and wooden mattresses, the composite mats may be the most attractive choice of soil protection material in construction activities.

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1 Introduction

Healthy natural and cultivated soils critically contribute to life on Earth by providing the majority of all food, feed and fibre used, storing carbon, regulating water, and hosting at least 25% of biodiversity, among others (European Commission (EC), 2021), but are threatened by human activities (Stolte et al., 2015). Soil threats such as soil sealing, soil pollution and soil compaction limit the extent to which a soil can fulfil its functions. The risk of soil compaction is particularly present during infrastructural construction activities, mainly because these activities involve the use of heavy machines, vehicles and equipment for transport or hauling of materials on natural and cultivated soils. For example, large excavators weigh 37–94 tonnes, and vehicles in transport can weigh up to 44 tonnes (The European Parliament and the Council, 2015). Additionally, traffic lanes or access corridors are often used intensely, which means that the soil is frequently stressed by wheeling with various vehicles and machines. As the schedule of construction may often be tight, activities may take place without careful consideration of soil strength.

Access materials such as timber and steel mats, sand beds and composite mats can be used in construction to support traffic/passages and to protect the soil. When used on traffic lanes or access roads, safety is increased as routes are marked, and surfaces stabilised. Driving on access materials also increases mobility as less energy is lost in the wheel-soil interface due to slip and soil distortion (Yong et al., 1984). When driving in wet conditions, access materials may prevent machines and vehicles from exceeding the soils bearing capacity and thereby prevent machines from getting stuck.

Access materials have thus been employed to protect soil, albeit mainly to avoid rut formations and prevent project slippages. Access materials may also protect the soil below the surface layer against compaction, as the wheel load is distributed over a larger area when driving on access material compared to directly on the soil surface. However, research of the effects of access material on the protection of the soil profile against compaction is largely lacking. This report summarizes a field experiment that was set-up to investigate the effects of different access materials on soil stress for tyre- and tracked motorised machines and vehicles used in construction activities.

1.1 Background

Soil compaction negatively affects physical, chemical and biological processes (Figure 1) and can enhance other soil threats, such as soil water erosion and the loss of soil organic matter (Stolte et al., 2015). The process of soil compaction causes an increase of the soil bulk density at the expense of soil porosity (Schjønning et al., 2013). The resulting reduction in the number and size of soil pores and an increase in soil strength, which restricts root growth, alters earthworm burrowing behaviour, and reduces the capacity to transport water and gases in and through the soil (Arrázola-Vásquez et al., 2022; Hamza and Anderson, 2005; Schjønning et al., 2015a). Impacts of soil compaction have been measured to one metre depth (Alakukku, 1999).

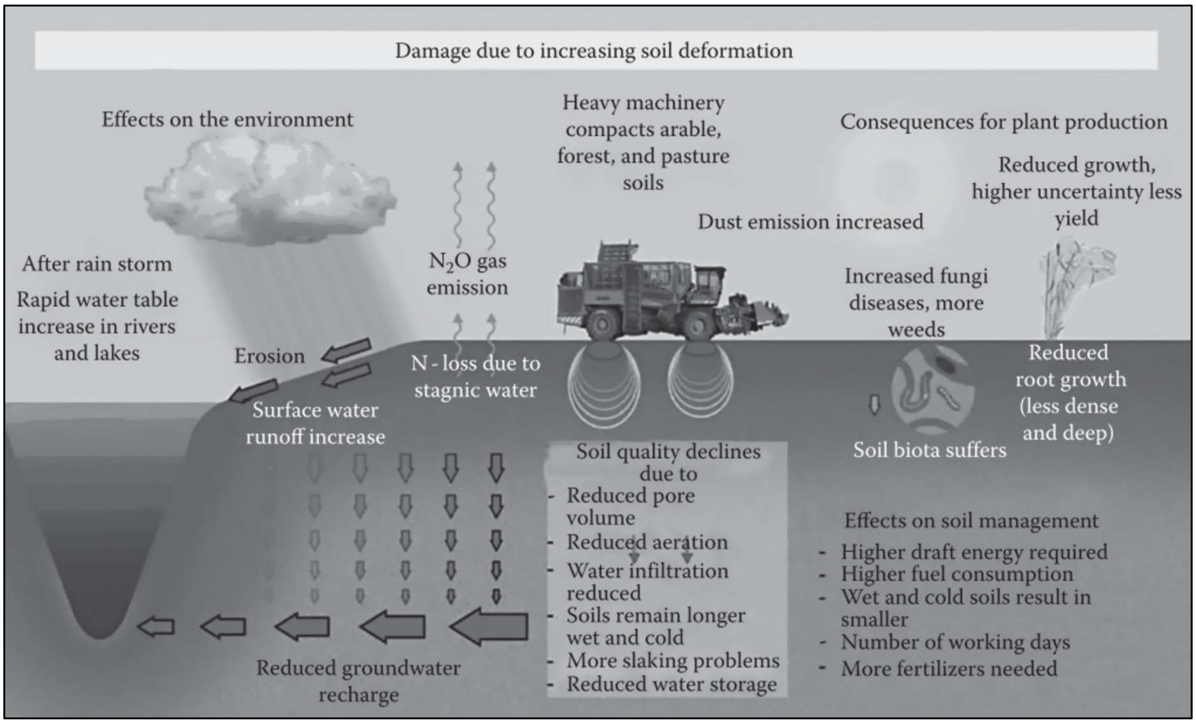

Figure 1. *Effects of soil compaction. From: Horn and Peth* (2011).

Soil compaction can occur within a few seconds during traffic, but its effects are long-lasting (Keller et al., 2017). Natural regeneration of the soil structure through wetting-drying cycles or bioturbation is slow (Berisso et al., 2012; Besson et al., 2013; Keller et al., 2021) and mechanical loosening of the structure, such as through soil tillage, is temporary, i.e. loosened soil is prone to re-compaction (Olesen and Munkholm, 2007; Schneider et al., 2017). Combining mechanical loosening and deep-rooted crops show greatest regeneration potential (Vanderhasselt, 2023), but the results of these studies do not cover more than two years after cultivation. The long-lasting effects of soil compaction and low recovery rates make compaction a major threat to soil health. It follows that prevention of soil compaction is vital for securing soil functions.

Soil compaction is, in principle, prevented if soil stress induced by machinery does not exceed soil strength. Soil strength depends on soil properties like bulk density, texture and organic matter, and is on a day-to-day basis strongly influenced by soil moisture; soil strength generally decreases with increasing soil moisture content (Saffih-Hdadi et al., 2009; Utomo and Dexter, 1981). The stress induced to soil by vehicles and machines is primarily dependent on the loading characteristics, such as contact area and wheel or axle load. A larger contact area leads to a lower mean ground pressure and lower peak stresses in the soil (Bailey et al., 1996; Schjønning et al., 2015b; van den Akker et al., 1994). However, the benefit of a larger contact area is limited when considering the reduction of stresses in the subsoil. At increasing depths, the level of stress relates more and more closely to wheel load instead (Arvidsson and Keller, 2007; Lamandé et al., 2007).

2 Materials and methods

2.1 Experimental site and setup

The effect of different access measures on soil stress was analysed based on measurements made in a field experiment with four types of construction machines driving directly on the soil and on three types of access materials. The field experiment took place on an arable site near Kallnach, Canton of Bern, Switzerland (47°00’52.8” N, 7°12’46.4” E) in July 2022. The field experiment was laid out as a split-plot design with two blocks (Figure 2). In each of the split-plot sections, four soil stress sensors were installed (section 2.2) for quantification of mean normal stress during traffic at 0.2 and 0.4 m depth under the initial soil surface.

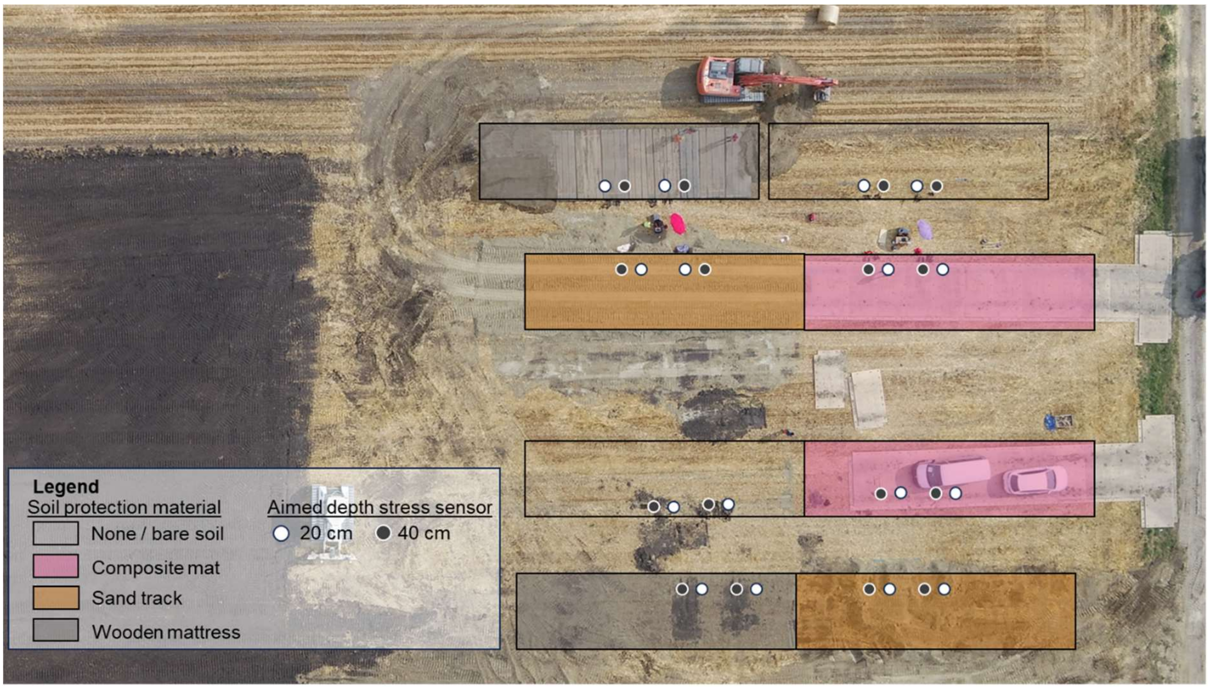

Figure 2. *Approximate experimental layout with a split-plot design in two blocks. Photo: copyright by Hurni Kies und Beton AG.*

2.1.1 Access materials

Three types of access materials were included: composite mats (DURA-BASE® Advanced Composite Mat System™, Newpark Mats & Integrated Services), sand track and wooden mattresses (Figure 3, Table 1). The sand tracks were created from a local mix of sand and gravel, distributed by an excavator and compacted by a 16-tonnes bulldozer.

Figure 3. *The access materials employed. From left to right: composite mats, sand track and wooden mattress. Photos by Loraine ten Damme.*

Table 1. *Characteristics of the access materials*

Access material	Length, m	Width, m	Height, m	Density, kg m^{-3}	Weight RM^{-1}, kg
Composite mats	2.13 [1]	3.96	0.10	247 [2]	186
Wooden mattress	0.40 [1]	5.00	0.30	345 [3]	518
Sand track	–	4.00	0.4–0.5	255 [4]	408–510

RM = running metre. Nd = not defined. [1] length per most individual segment. [2] based on Newpark Mats & Integrated services, n.d. [3] based on average for spruce. [4] assumed, based on a measured density of 266 kg m^{-3} after the experimental traffic.

2.1.1 Experimental traffic by construction machines

Experimental traffic was performed by two motorised machines with a metal-track undercarriage system, a 16-tonnes bulldozer and 21-tonnes excavator, and by two vehicles equipped with tyres, a 11+29-tonnes tractor-trailer combination and a 40-tonnes lorry (Figure 4, Table 2). Both groups are referred to as (construction) machines. The machines passed the experimental area at < 5 km h^{-1}. The order of passage was fixed (dozer, excavator, tractor-trailer and lorry). With each machine, four passes were made per plot.

Figure 4. *The four different construction machines (Table 2) for which soil stress measurements were collected. Photos by Loraine ten Damme and Janosch Gerber.*

Table 2. *Key-characteristics of the construction machines employed.*

Machine	Axle	Category	Dimensions	*A* [m²] [1]	*F* [Mg]	p_{tyre} [kPa]	p_{mean} [kPa]
Bulldozer	Right	Steel track	3.2 * 0.86 [2]	2.75	8.0	-	29
Excavator	Right	Steel track	3.9 * 0.6 [2]	2.34	10.5	-	45
Tractor	Front	Tyre, driven	540/65 R34	0.37	1.6	165	42
Tractor	Rear	Tyre, driven	650/75 R38	0.53	4.2	190	78
Trailer	Front	Tyre, rolling	650/50 R22.5	0.45	4.7	365	102
Trailer	Middle	Tyre, rolling	650/50 R22.5	0.42	5.0	395	117
Trailer	Rear	Tyre, rolling	650/50 R22.5	0.45	5.0	375	109
Lorry	Front	Tyre, driven	385/65 22.5	0.18	3.5	700	191
Lorry	Second	Tyre driven	385/65 22.5	0.18	3.3	700	180
Lorry	Third	Tyre, dual driven	315/80 R22.5	0.09*2	4.7/2	700	256
Lorry	Fourth	Tyre, dual driven	315/80 R22.5	0.09*2	5.3/2	700	288
Lorry	Rear	Tyre, driven	385/65 22.5	0.18	3.8	700	207

A = ground contact area; *F* = static steel track or wheel load; p_{tyre} = tyre inflation pressure; p_{mean} = mean ground pressure calculated from *A* and *F*. [1] = track areas are calculated from their dimensions; tyre area is estimated with the FRIDA model (Schjønning et al., 2015b, 2008). [2] = length (m) * width (m) of ground contact.

Bolling probes (Bolling, 1987) were used for quantification of mean normal soil stress (σ_m) during traffic at 0.20 and at 0.40 m depth from the soil surface. The probes consist of a rubber membrane head (inner diametre 10 mm, length 150 mm) at the end of a tube with similar dimetre as the membrane head (Figure 5). These were filled with an incompressible fluid (water) and connected to a syringe, with which an initial pressure was applied to ensure good sensor-soil contact. Closing off the valve leads the inclusion pressure (p_i) to be measured in a pressure gauge transducer between the tube and the syringe. The transducers were connected with a data bus, and pressures were recorded approximately every 0.12 seconds. This resulted in stress-curves such as shown in Figure 6.

For each access material within each block, *i.e.*, in each plot, two probes were installed per depth. These were inserted in the soil in holes drilled under predefined angles guided by a frame. Following the Pythagorean theorem, the positions of the membrane heads were known. The soil and access material's surface were marked to guide the drivers straight over the sensors with the centreline of tracks and tyres – with the exception of the tractors front tyre, which was smaller than the rear tyre, and which is therefore excluded from the data.

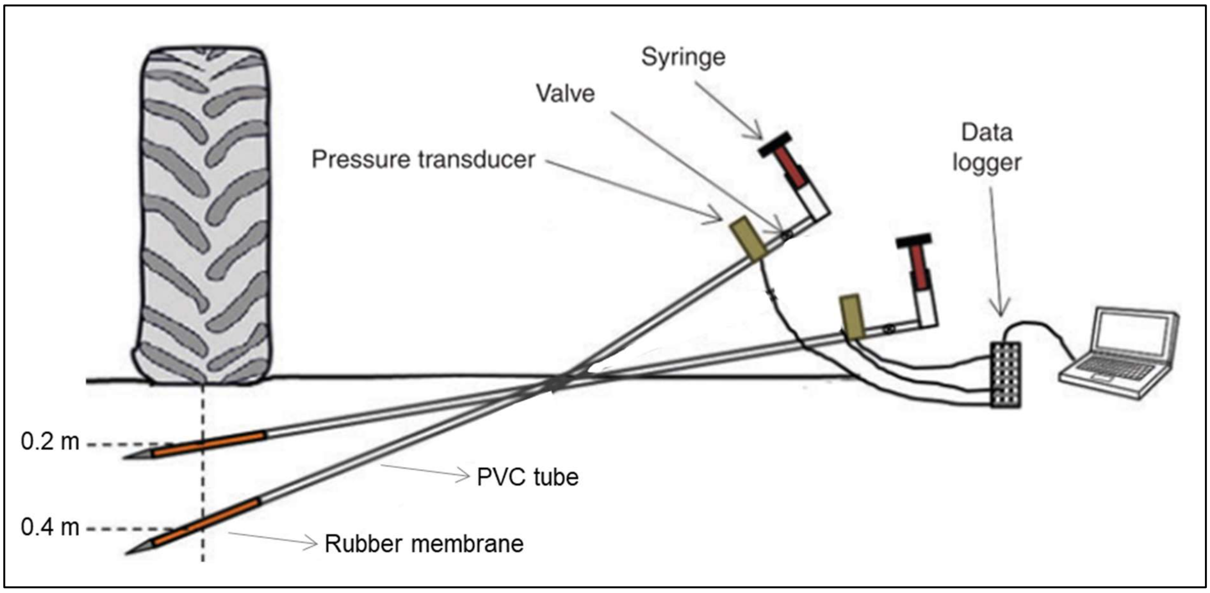

Figure 5*. Set-up of the soil stress measurement system. Adapted from Naderi-Boldaji et al.* (2018)*.*

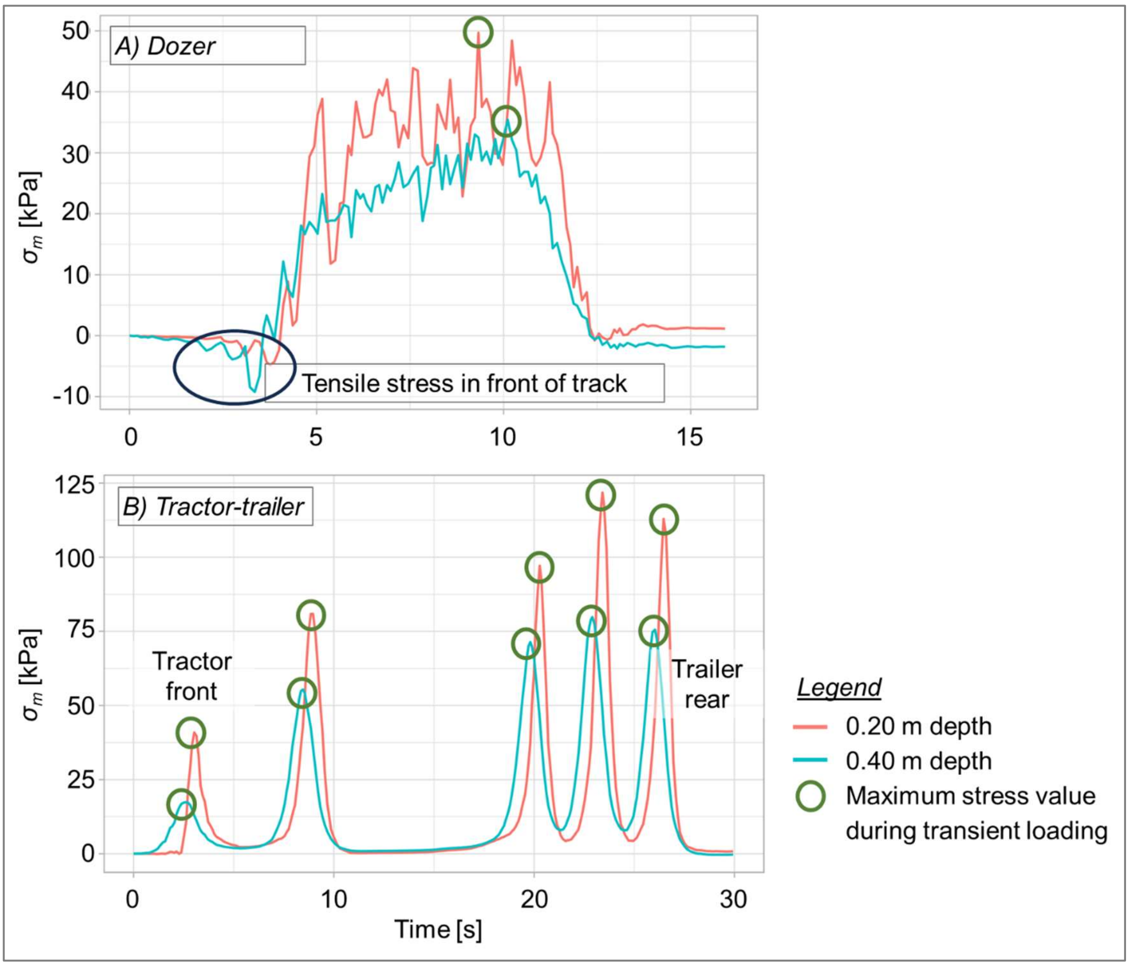

***Figure 6**. Typical stress-curves for A) the dozer and B) the tractor-trailer combination driving directly on the soil surface. Note the different time and stress-scales in the two plots. The maximum stress values are used for analyses.*

The inclusion pressures were converted to mean normal stress (σ_m, Eq. 1) following the approach outlined by Berli et al. (Berli et al., 2006), who showed that the conversion factor k_s as suggested by Bolling (Bolling, 1987) becomes a function of Poisson's ratio (v) of soil (Eq. 2). The Poisson's ratio was estimated from soil mechanical tests on undisturbed soil cores (Eggers et al., 2006) sampled from 0.20 and 0.40 m depth (section 2.2).

$$\sigma_m = \frac{p_i}{k_s}$$ **Eq. 1**

$$k_s = \frac{3(1-v)}{1+v}$$ **Eq. 2**

The maximum mean normal stress for each wheel (tyre or track) was extracted to study the effect of access materials on the reduction of soil stress, both by magnitude as well as in relative reduction using the log-response ratio (Eq. 3),

$$RR = log\frac{x_R}{x_C}$$ **Eq. 3**

where x_R is the response mean, the arithmetic mean of four passes for each axle and probe (*i.e.,* per plot and depth), for the three access materials, and x_C is the control mean, the arithmetic mean during traffic directly on the soil surface. A single measurement (dozer on sand bed, 0.4 m depth, third pass) was excluded from the dataset, as the mean normal stress (252 kPa) was 550% of the third quartile of all data points (45 kPa) and 780% of the third quartile of the data points for the dozer on sand at 0.4 m depth (32 kPa).

2.2 Soil mechanical characterisation

Soil cores (471 cm^3; 6 cm high, 10 cm inner diametre) sampled at 0.2 and 0.4 m depth in undisturbed areas in between the plots were used for measurements of the soil's Youngs modulus (*E)* and the Poisson's ratio (*v*) – both soil elastic properties – of the reference soil, *i.e.*, of the soil prior to wheeling. The properties were obtained from stress-strain curves from compression tests performed with the 08.67 Compression test apparatus set (Royal Eijkelkamp, Giesbeek, The Netherlands).

2.2.1 Youngs modulus

The Youngs modulus was deducted from stress-strain curves of unconfined compression tests, *i.e.*, on soil samples taken out of their cylindrical ring. Each sample was stepwise loaded from 0 to 30 kPa with a 5-kPa increment, then unloaded, reloaded similarly but with an additional loading step at 50 kPa. Each load was maintained on the soil core for one minute. The Youngs modulus of individual cores was defined as the slope of the linear part of the reloading curve. The Youngs modulus of the reference soil was calculated as the geometric mean of the cores sampled at 0.2 and 0.4 m: 2'072 and 3'936 kPa, respectively.

2.2.2 Poisson's ratio

The Poisson's ratio was defined using Eq. 4 following Eggers et. al (Eggers et al., 2006), based on the slope ($\frac{\varepsilon_z}{\sigma_z}$) of the linear part of the reloading curve of confined compression tests, *i.e.*, soil samples contained in their cylindrical ring, and the Youngs modulus (section 2.2.1).

$$v = \frac{1}{4}\left[\frac{\varepsilon_z E}{\sigma_z} + \left\{\left(1 - \frac{\varepsilon_z}{\sigma_z} E\right)\right\}^{0.5} - 1\right] \qquad \textbf{Eq. 4}$$

In the confined compression tests, samples were stepwise loaded and reloaded to 0, 5, 10, 15, 30 and 50 kPa, followed by a 75-kPa load during reloading. Each load was maintained on the soil core for one minute. The Poisson's ratio of the reference soil was calculated as the geometric mean of the cores sampled at 0.2 and 0.4 m: 0.33 and 0.43, respectively.

3 Results and discussion

3.1 Access material affects stress propagation into the soil

During transient loading directly on the soil surface, *i.e.*, without access material, the magnitude of stress decreased with increasing depth Figure 7. Under access materials, however, the reduction of stress with increasing depth was smaller or missing (Figure 7). This can be seen in Figure 7 by comparing the datapoints with the 1:1-line; the line at which mean normal stress at 0.2 and 0.4 m depth would be equal. The further the datapoints lay away from this line (obvious for None), the bigger the difference between the magnitude of stress at the two depths. Differences between stress at 0.20 and 0.40 m depth was generally larger for Composite mats than for Wooden mattresses and the Sand track, which indicates a difference in the stress-reduction with depth between access materials. The difference may be explained by differences in thickness of the access material (Table 1) and by differences in the elasticity or stiffness of a material, which affects the stress transmission through the material.

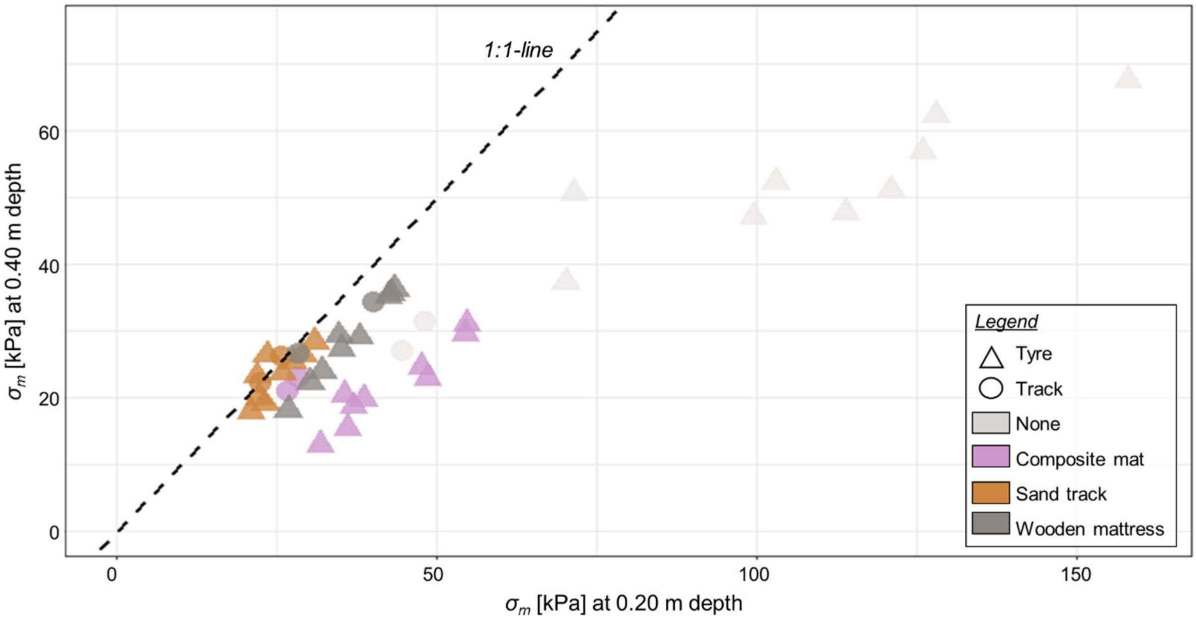

Figure 7. *Relationship between average mean normal stress at 0.20 and 0.40 m depth. The average is taken across blocks and passes. At the 1:1 line, stress at 0.20 and at 0.40 m depth are equal.*

3.2 Access material affects the magnitude of mean normal soil stress

Mean normal soil stress was affected by using access materials, but mostly during transient loading of the wheels with tyres: the tractor’s rear axle and trailer and, in particular, the lorry had the greatest reductions of the magnitudes of soil stress (Figure 7–9). For the tracked machines, the dozer and excavator, the use of access materials reduced mean normal soil stress at 0.20 m depth, but not at 0.40 m depth (Figure 8, Figure 9). The lack of reduction at 0.40 m depth for the tracked machines could be a result of the dimensions of the tracks – being both wider and longer than most of the tyres. At increasing depths, the magnitude of stress is affected by a larger (contact) area. For the tracks, the track-soil contact area contributing to soil stress may be larger at 0.4 than at 0.2 m depth. Moreover, the level of stress under the tracked vehicles was generally low. This is explained by the low mean ground pressure, due the large contact areas of the tracks (Table 1).

3.2.1 Composite mats

The composite mats generally reduced the magnitude of mean normal soil stress (Figure 8). For the tracked machines, the composite mats were slightly more effective in reducing mean normal stress at 0.20 than at 0.40 m depth, as seen from the smaller (more negative) response ratio at 0.20 m depth in Figure 9. This is caused by the reduction of mean normal stress with increasing depth when driving directly on the soil surface, while the magnitude of stress under the access materials is comparable at the two depths (Figure 8). Contrastingly, from Figure 9 it appears that the composite mats reduced stress during transient loading of wheels with tyres more effectively at 0.40 compared to at 0.20 m depth. Here one must, however, consider the larger variation of mean normal stress at 0.40 m depth under the soil surface with access material (Figure 8).

3.2.2 Sand track

Driving on the sand track instead of directly on the soil reduced mean normal soil stress for the tracked construction machines at 0.20 m depth, and for the machines with tyres at 0.20 and 0.40 m depth. (Figure 8, 9). The effect of the sand track on mean normal soil stress at 0.20 and 0.40 m depth during traffic with the tracked machines was comparable to the effect of the composite mats. Yet, the sand track was approximately four to five times as thick as the composite mats, hence the distance from the track to the stress probes larger, and the magnitude of soil stress is known to decrease with increasing depth. This indicates that the sand track was, based on volume of access material, less effective in reducing mean normal soil stress than the composite mats. For the tyres, mean normal soil stress was approximately 50% lower under the sand track compared to the composite mats at 0.20 m depth (Figure 8), hence the effectiveness of reducing soil stress larger (Figure 9). At 0.40 m depth, differences in soil stress during transient loadings with the tyres on the sand track or the composite mats were again negligible.

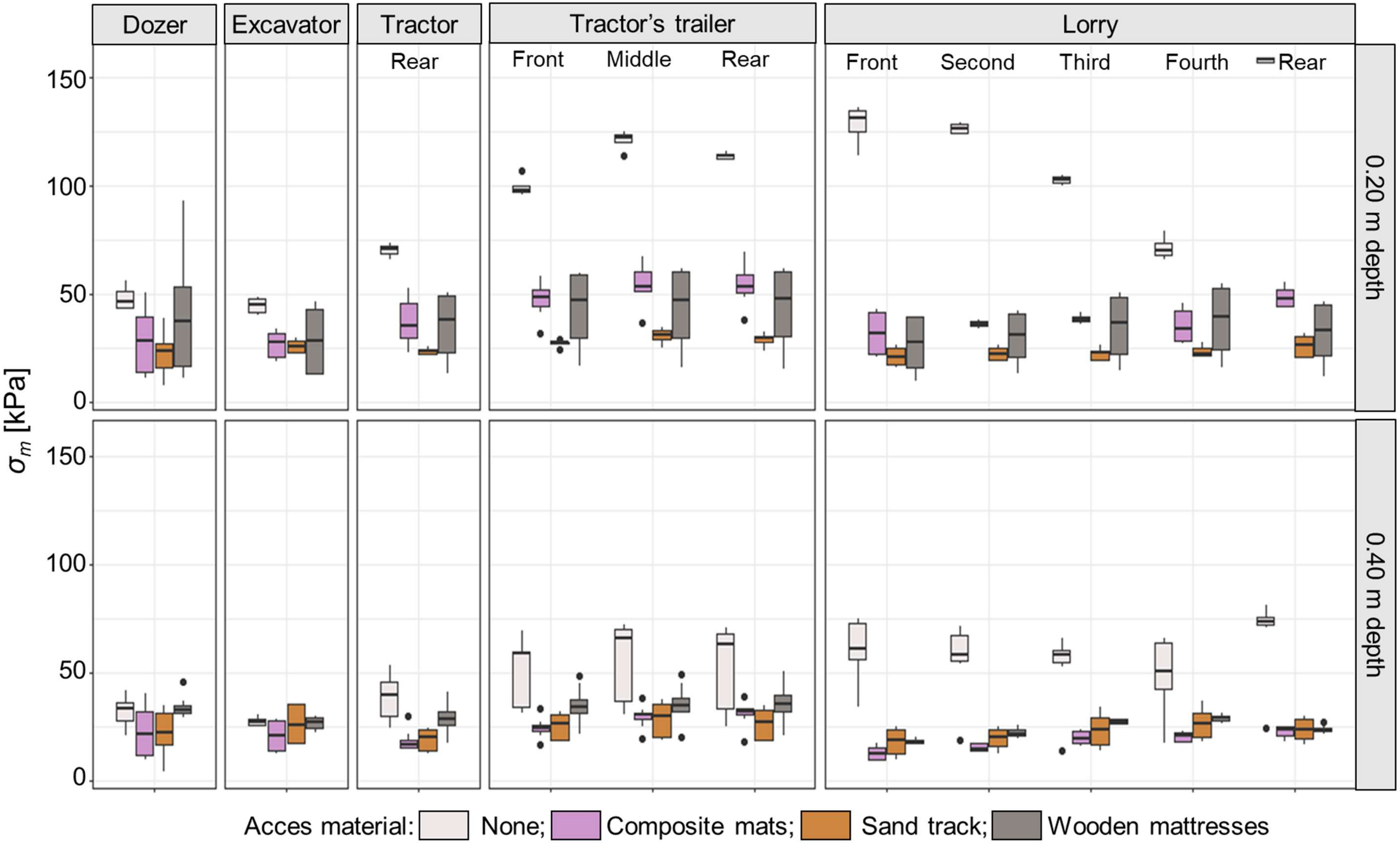

Figure 8. *Boxplot of mean normal stress measurements per depth, machine and axle, and access material.*

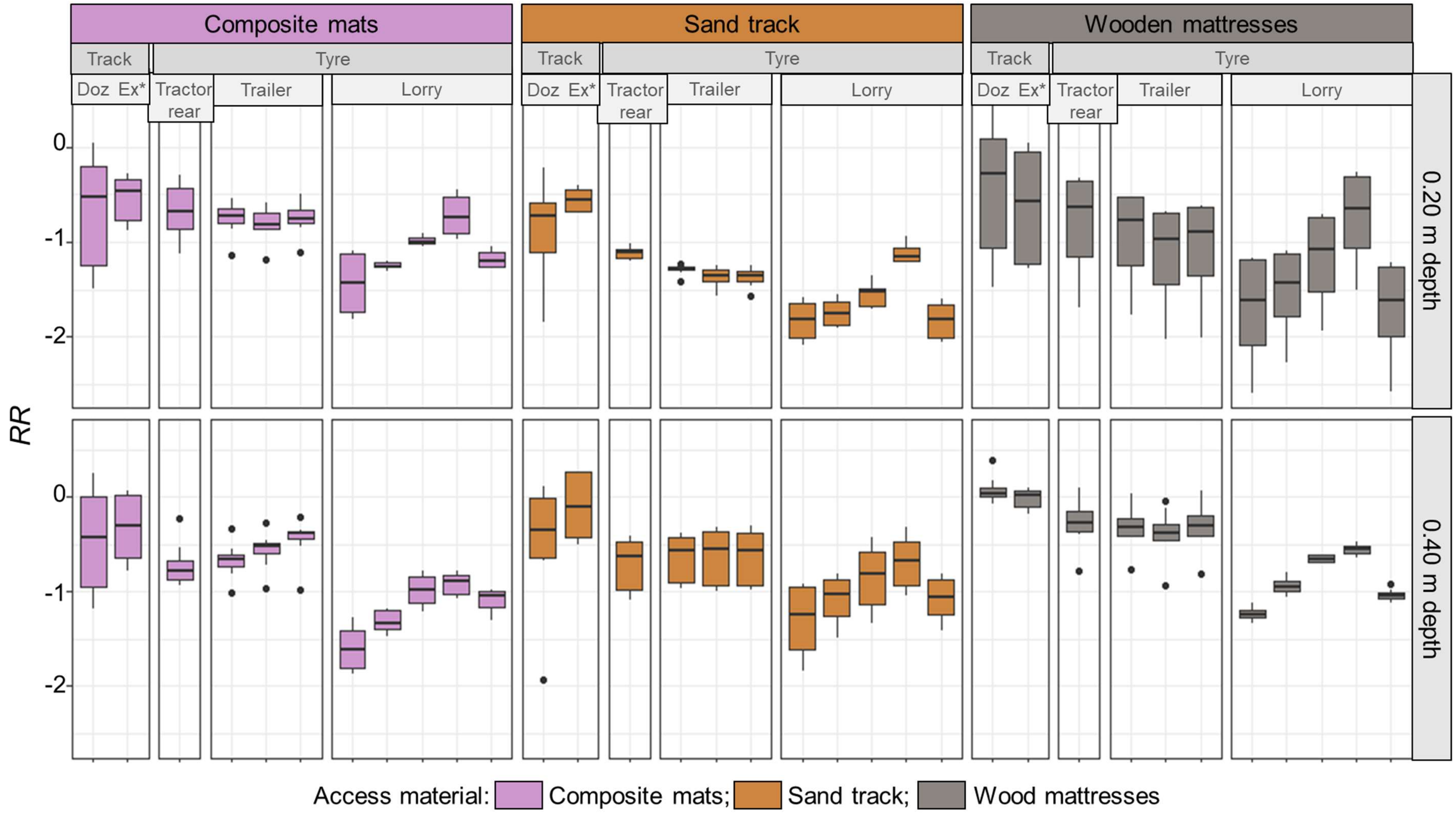

Figure 9. *Response ratio (RR, Eq. 3) of mean normal soil stress at 0.20 and 0.40 m depth per machine and axle for the three different access materials employed. A RR > 0 means that the stress under the protection material was higher than for driving directly on the soil surface, whereas values < 0 indicate that the stress under protection material was lower than measured when driving directly on the soil surface.*

3.2.3 Wooden mattresses

The stress measurements made under the wooden mattrasses showed a large variation at 0.20 m depth, across all machines and axles (Figure 8). This may be caused by slight rotations during wheeling of the individual logs that make up the mattress (Figure 10): looking at the machine driving on the logs from the side, a log rotates anti-clockwise at initial contact, then levels and is pushed downwards by the total wheel load, and by the wheel leaving the log, the log is rotated clockwise. The stress measurements could be of different magnitude depending on their exact position beneath a single log, and the highest stress might not always have been measured at 0.20 m depth. At 0.40 m depth, the range of the magnitude of the measurements is narrower (Figure 8). Presumably, the potential effect of rotating logs is reduced.

For the tracked vehicles, the wooden mattresses did not reduce mean normal soil stress. In fact, for the dozer some measurements exceeded the magnitude of driving directly on the soil surface (Figure 8). This may be due to the smaller contact area of the tracked vehicles when driving on the wood compared to driving on soil or sand, as the lugs of the track do not penetrate the wood. It is then the surface of the lugs, not the tracks' dimensions, that make up contact area through which the vehicle's load is distributed over the logs. Consequently, one expects a higher mean ground pressure and higher soil stress. However, the lugs cannot penetrate the Composite Mats either, yet for the Composite Mats a small reduction of soil stress was observed (Section 3.2.1). This difference may relate to the fact that the Composite mats interconnect whereas the Wooden mattrasses exist of single logs connected by a chain, which may affect the stress propagation through the material.

For the tractor-trailer combination, the wooden mattresses reduced mean normal stress at 0.20 m depth considerably. However, at 0.4 m depth, the effect was limited (Figure 8) with a response ratio > -0.5 and crossing through zero (Figure 9), meaning that in some cases the stress during driving in the wooden logs was higher than driving directly onto the soil surface. During transient loading by the lorry, mean normal soil stress was notably reduced by the use of the wooden mattresses, both at 0.20 and 0.40 m depth (Figure 8, 9).

Figure 10. *Schematical drawing of the rotation of individual logs during wheeling. Not to scale. See text for explanation.*

3.3 Summary and further considerations

The composite mats and sand track reduced soil stress better than the wooden mattresses. Taking into consideration the differences in thickness of the composite mats and the sand track (0.10 and 0.40–0.50 m, respectively, Table 1), the reduction of mean normal soil stress by the composite mats is greater than the reduction by the sand track. Moreover, the weight per running metre was lower for the composite mats compared to the sand track (186 and 408–510 kg RM^{-1}, respectively, Table 1), hence fewer trucks are needed to deliver the material for covering an area with access material. The access roads made up of composite mats are quicker operatable than the sand track, which need to be transported by a tractor-trailer or lorry, build by an excavator and compacted by a dozer. Though there are other considerations to consider (*e.g.*, availability of access material), composite mats may be the more attractive choice than sand tracks in construction activities.

4 Conclusion and recommendations

Driving on access materials instead of directly on the soil surface reduced the level of mean normal stress in the soil, and thereby helped reducing the risk of soil compaction. The reduction of mean normal soil stress differed between the access materials, depth and type of undercarriage (*i.e.*, track or tyre):

- The reduction of mean normal stress at 0.20 m depth was largest when driving on the sand track (0.40–0.50 m thick), both for the machines with tracks and with tyres.
- The reduction of mean normal stress at 0.20 m depth by the use of access materials was greater for the machines with tyres than for those with tracks.
- At 0.20 m depth, the reduction under the composite mats (0.10 m thick) and the wooden mattresses (0.30 m thick) was comparable, although the variation in stress under the wooden mattrasses was much greater than under the composite mats.
- At 0.40 m depth, access materials helped reducing mean normal soil stress during transient loading by tyres, but there was no effect during loading by the tracked vehicles.
- The reduction of mean normal stress at 0.40 m depth during transient loading by the tyres was comparable between the composite mats and sand tracks, which outcompeted the wooden mattresses.
- While the reduction of mean normal soil stress during the transient loading of the machines with tracks was limited, it did prevent soil rutting.

Taking into consideration the thickness and weight per running metre of the composite mats, sand track and wooden mattrasses, the composite mats may be the most attractive choice of soil protection material in construction activities.

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