Effect of joint dip on the transmission of stress waves from a moving point load in a parallel jointed rock mass

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ABSTRACT: This paper presents a comparison between the response of an isotropic continuum and a jointed discontinuum when subject to a moving point load source. A numerical model was setup in the Universal Discrete Element Code (UDEC) and a tunnel was modelled longitudinally as nodes within the model. Discontinuum models with four different joint angles and a single isotropic continuum were analysed with the relatively near field and far field vertical displacement from each model recorded. It was found that the discontinuum models can show more or less displacement than the isotropic continuum depending on the joint angle. The patterns of the response were found to be different in the far field and near field. Conclusions were drawn relating to considerations for the best practice for commercial modelling of railway vibrations.

Keywords: Jointing, Rock Engineering, Moving Load, Underground, Vibrations.

1 INTRODUCTION

Underground rail vibrations are a well-known issue in urban environments. Vibrations propagating through the ground can cause a nuisance to residents living close to a line and interfere with sensitive structures, such as recording studios and scientific laboratories (Connolly et al. 2016). Many research studies have been conducted investigating rail vibrations in soft ground conditions; however, there has been very little research carried out analysing the propagation of vibrations from tunnels in jointed rock masses.

Stress waves propagating through a jointed rock mass interact with joints, being reflected and refracted to different degrees depending on properties of the wave and joint and the angle of incidence between the wave and joint. Problems such as this have been widely studied in literature with analytical solutions being derived for a variety of situations (Cai & Zhao 2000; Pyrak-Nolte et al. 1990; Zhao et al. 2008). Studies into the transmission of stress waves across joints have focused on a static loading location, while realistic dynamic situations typically involve moving loads. In such cases the load will move relative to a joint, changing the angle of incidence, and therefore degree of reflection and refraction of the wave.

This study numerically investigates the role of jointing in the excitation of a rock mass subject to a moving point load in the near field and far field using the discrete element method in the Universal Discrete Element Code (UDEC) (Itasca 1990). UDEC is capable of accurately modelling jointed rock masses and has been widely used for studying dynamic interactions of jointed rock masses and stress waves (Eitzenberger 2012). A 2D plane strain full space model is used for the analysis. A tunnel is modelled longitudinally, in accordance with the concept adopted by Yuan et al. (2015). However, as the aim is to analyse the relative effect of joint orientation when subjected to a moving load, instead of a realistic ground response, the tunnel is approximated as a string of internal modelling nodes. For this work the near and far field are relative terms, with the near field taken as the location of modelling nodes, while the far field is taken at an arbitrary 20m from the loading location.

2 METHODOLOGY

A model was set up in UDEC which was used for all analyses by changing the presence and orientation of the joints (Figure 1a). Four individual discontinuum analyses are conducted with joint angles of 0, 45, 90 and 135° (Figure 1b). The symmetry of the model allows these four analyses to give the response of models with joints between 0° and 180°. Joint angles are measured anti-clockwise from horizontal; therefore, a 0° joint is horizontal and a 90° joint is vertical. All joints were parallel at a spacing of 2m within 10m of the load location, with the spacing increasing to 10m at greater than 10m from the loading to reduce the run time of the model (Figure 1a). A complimentary continuum analysis was run as an unjointed comparison, using the intact block stiffness used in the discontinuum analysis for the entire model. This represents an isotropic continuum model, a common assumption used in railway vibration analysis (Connolly et al., 2016). Absorbing boundary conditions were modelled in order to prevent spurious reflections from the model boundaries from significantly affecting the results.

A moving point load was modelled as travelling from left to right at a 50 m/s along the line marked "tunnel" in Figure 1a. An arbitrary 100N force was applied to modelling nodes along the "tunnel", which is a construction line within the model. The 100N force is not related to any realistic train loading and the construction line will not behave like a realistic tunnel; however, for a comparison analysis such as this this set up will be sufficient to achieve meaningful results.

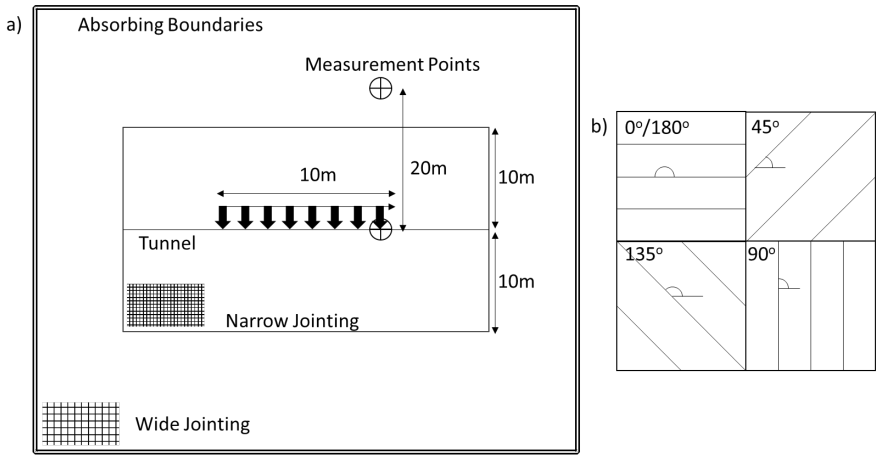

Figure 1. (a) Model used for analysis (not to scale). Crossed circles = measurement points, solid vertical arrows = loading locations. (b) Joint orientations.

All models used the same properties, shown in Table 1, and adopt the Mohr-Coulomb failure criterion for blocks and the Coulomb slip criterion for joints. All models were analysed as perfectly elastic, which is a reasonable assumption for the small degrees of strain which will occur due to the loads applied in the model, and indeed realistic strains induced by railway vibrations (Ruiz et al., 2019). The properties for the intact blocks are Basalt from UDEC's inbuilt database of properties (Itasca, 1990), with the joint properties user defined. High shear properties (friction and cohesion) are applied to the joints to ensure that only elastic deformation occurs.

Table 1. Intact Block and Joint Properties used in modelling.

Property		Value
Elastic Stiffness – Block	[GPa]	34.9 GPa
Shear Modulus – Block	[GPa]	13.2 GPa
Cohesion – Block	[GPa]	66.2 MPa
Friction – Block	[°]	31°
Tension – Block	[MPa]	13.1 MPa
Density – Block	[kg/m^3]	2700 kg/m3
Joint normal stiffness	[GPa]	1 GPa
Joint shear stiffness	[GPa]	1 GPa
Joint Cohesion	[GPa]	1 GPa
Joint Friction	[°]	45°

Material damping in all models was set to zero. This ensures that any differences being observed is due to the presence of jointing and not other factors. This approach has been adopted in previous studies of stress wave interaction with jointed rock masses in UDEC (Eitzenberger 2012; Holmes et al. 2022). Despite this, due to the 2D nature of the model and the 1D nature of the point load there is still the possibility for geometrical damping to occur as the wave front spread out into the model. However, this will be the same for both models and should not adversely affect the results.

Vertical displacement histories were recorded at the same location in each model (Figure 1a). Near field displacements were recorded at the final position of the moving point load, with the far field displacements being recorded 20m above this. The maximum displacement recorded at these measurement points were taken as the displacement for that model.

3 RESULTS

Table 2 shows the results for the numerical modelling of the moving point load in the jointed and unjointed cases. Figures 2 and 3 show this data graphically. Table 2 shows that in all cases the near field displacement is at least an order of magnitude greater than the far field displacement of the same model. When comparing the different cases, Figure 2 shows that the displacement in the discontinuum models is greater than the continuum model for all joint angles, except 90° joints. A 90° joint gives the lowest displacement, while a 0° or 180° joint give the greatest displacement. Joint angles of 45° and 135° give intermediate displacements, with the 135° joint giving a slightly greater displacement than a 45° joint.

Table 2. Results from modelling of moving point load. All displacements are vertical displacements.

Model	Near Field Displacement (m)	Far Field Displacement (m)
Discontinuum joints at 0°	1.757E-07	1.026E-10
Discontinuum joints at 45°	4.695E-08	3.931E-09
Discontinuum joints at 90°	1.326E-08	3.329E-09
Discontinuum joints at 135°	5.871E-08	6.749E-11
Isotropic Continuum	2.697E-08	1.537E-09

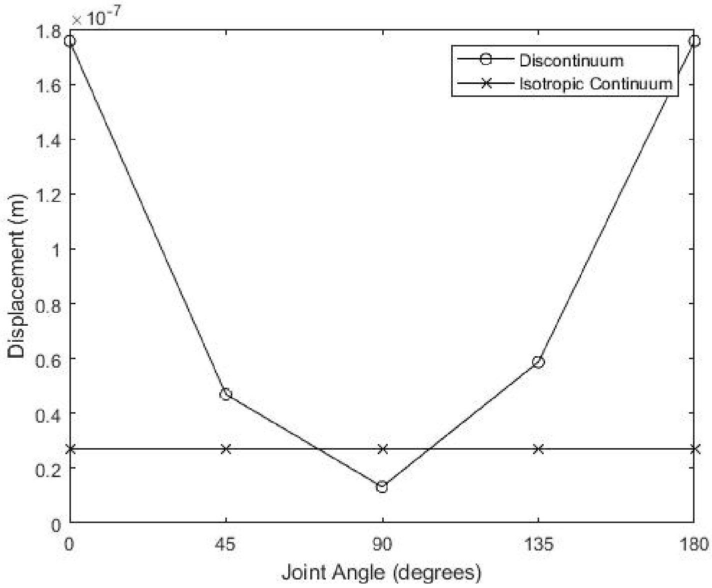

Figure 2. Near field vertical displacement of model due to moving point load.

Figure 3 gives a different pattern to that observed in Figure 2 with the isotropic continuum showing more displacement than the jointed models in some cases and less in others. Joint angles of 0^o, 135^o and 180^o show less displacement, while joint angles of 45^o and 90^o show more displacement. This contrasts with Figure 2 where the two joint angles showing the greatest displacement in Figure 3 show the least displacement in Figure 2.

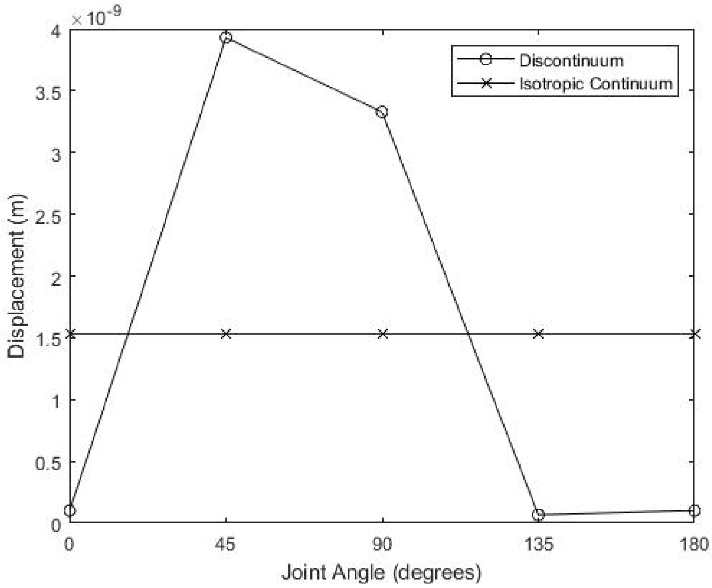

Figure 3. Far field vertical displacement of model due to moving point load.

4 DISCUSSION

Figures 2 suggests that in the near field the displacement increases the closer the joints are to horizontal. The reason behind this is likely to be due to reflections from the joints close to the loading location preventing the energy from the stress waves from escaping from the area close to the loading location. As the joints become angled away from 0^o there is more scope for energy to be channeled away from the loading location; therefore, reducing the amount of energy in the near field. In the case of the 90º joints there is limited energy reflected back towards the loading location; therefore, causing the low displacement in the near field.

Figure 3 shows that the 90º joints show an elevated vertical displacement in the far field. The vertical joints will prevent energy from being transmitted laterally in the model, instead channeling energy from the stress waves vertically. Due to this the displacement in the far field is elevated.

The joint angle relative to the direction of loading is expected to account for the difference in the far field displacement between 45º and 135º joints (Figure 3). At 135º the joints are dipping downwards in the same direction as the moving load, which travels from left to right, with the opposite the case for the 45º joints (Figure 4). With the moving load travelling into the plane of the joints more energy may be reflected and trapped in the case of the 135º joints, while more energy can be deflected away by the 45º joints. This deflection of energy may be seen in the far field in Figure 3, where the 45º joints show a greater displacement than other joints angles. However, it should be noted that if the direction of the moving load is reversed in the 45º model it becomes identical to the 135º model, in respect to the relative joint angle to the direction of the load (Figure 4). Therefore, the if the load was moving from right to left the 45º model would be expected to perform identically to the 135º model. It can be assumed that the elevated displacement in the 45º case is because the causes of the elevated displacement in the 90º case are combined with deflection of energy previously described.

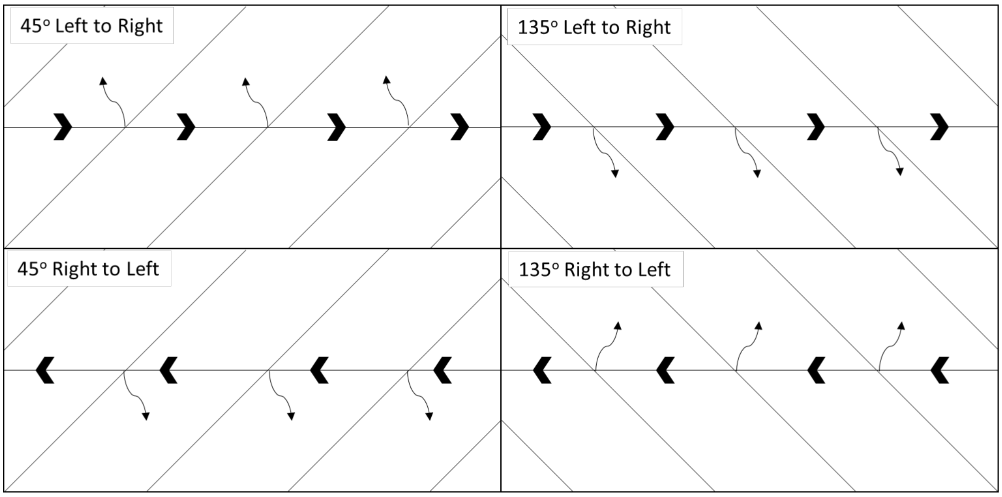

Figure 4. Joint angle (thin black line) relative to moving load (solid arrows) with direction of deflection (curved arrow).

5 CONCLUSIONS

Figures 2 and 3 show that the presence of joints within a model significantly effects the displacement in the near and far fields when a moving point load is applied within a 2D plane strain full space. The near field displacement has been found to be greater in the discontinuum model than the continuum model for all joint angles due to reflection of energy from joints. In the far field the joint angle relative to the direction of the moving point load plays a role in the magnitude of the vertical displacement. Vertical joints and the up-dip direction of the joint being in the direction of travel of the load causes greater vertical displacements in the far field.

The implications of this study are that it is necessary to model a tunnel embedded in a jointed rock mass by explicitly modelling joints, rather than using commonly assumed isotropic continuum techniques to represent the rock mass. In the near field assuming that a model is an isotropic continuum, as opposed to a discontinuum, will lead to an under-estimate of ground displacements. In the far field the effect depends upon the joint angle; however, it is also likely to lead to an inaccurate result. In the case of tunnels which can have loads moving in different directions, such as it the case with railway tunnels, the joint angle relative to the travel direction can cause significant differences in vertical displacement of the ground in the far field. Therefore, it would be pertinent to model loads moving in both directions when tunnels are embedded in jointed rock masses due to the risk of increased ground displacements in one direction.

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