Li, X. F. *et al*. (2018) ***Géotechnique Letters* 8**, 190–194, https://doi.org/10.1680/jgele.18.00042

Effect of joint thickness on seismic response across a filled rock fracture

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This study aims to investigate the influence of joint thickness on seismic response across a filled fracture with strong nonlinear deformability. To simulate seismic attenuation of thicker joints subject to high-amplitude stress waves, the split Hopkinson pressure bar is utilised to generate normally incident *P* wave and the dry quartz sand is used to simulate the filled joints. Three joint thicknesses – that is 5, 10 and 15 mm, are studied under identical incident waves. The stress–strain response of the filling materials is described by Barton–Bandis model having different loading–unloading behaviours. The initial stiffness and the maximum allowable closure of the joints changing with the joint thickness are studied. The thicker joints result in lower initial stiffness and cause lower seismic wave transmission across the fracture. The high-amplitude stress strengthens the nonlinearity of the filling materials and increases the stiffness. Besides, the seismic attenuation factor *Q*, derived from the energy dissipation, is lower than that computed by the transmission coefficient due to the frequency filtering.

KEYWORDS: earthquakes; laboratory tests; rocks/rock mechanics; seismicity

NOTATION

A_{bar} cross-section area of the bar
c_{bar} wave velocity of the bar
$d_{\max}$ maximum allowable closure of the joint
E_{bar} elastic modulus of the bar
E_{ini} initial modulus
e sum of the input energy which is equal to W_{I}
l loading process
Q_{am} maximum stresses in incident wave and transmitted wave
Q_{er} intrinsic attenuation and apparent attenuation
ul unloading process
$\Delta e = W_{\text{I}} - W_{\text{T}}$ amount of energy dissipated per cycle excitation
ε strain responded by the joint
σ stress responded by the joint
σ_{I} stress for the incident bar
σ_{R} stress for the reflected bar
σ_{T} stress for the transmitted bar

INTRODUCTION

Rock discontinuities exist in the form of joints, faults, bedding planes and affect the physical, mechanical and seismic response of rock masses. These discontinuities reduce the stiffness and ultimate strength of the rock mass, aggravate the deformability and permeability and make the rock masses mechanically unstable. When seismic waves propagate across the fractured rocks, the nonlinear and discontinuous deformations play a vital role on the seismic wave attenuation and rock mass stability response. Filled joints, existing as a composition of sand, clay or pulverised rock, are found to be ubiquitous in nature at a scale of thickness varying from a fraction of a micron to several metres (Sinha & Singh, 2000). The physical properties of filling materials (i.e. the water content, filling material composition and grain size) influence the stiffness of the joints (Bandis *et al*., 1983; Sinha & Singh, 2000) and as a result complicate stress deformation behaviour. The dynamic response of the sand-filled fractures is found to be nonlinear and the thickness is non-negligible considering that the initial mass may affect the wave propagation (Li & Ma, 2009). According to experimental investigations on the filled joint used by modified split Hopkinson pressure bar (SHPB) technique, the dynamic response of joints can be summarised as: (a) the filled joint commonly behaves as nonlinear (Li & Ma, 2009; Li *et al*., 2010) with different loading/unloading behaviours (Fan & Wong, 2013); (b) the boundary condition is equivalent to stress and displacement discontinuous (Zhu *et al*., 2011; Wu *et al*., 2013) considering the inertial effect of the fillings; and (c) the filling thickness (Li & Ma, 2009; Li *et al*., 2010), filling materials (Wu *et al*., 2014), loading rate (Wu *et al*., 2012a, 2012b), the pre-compaction of filling materials (Li *et al*., 2010), frequency and amplitude of the incident wave (Li *et al*., 2010) and the water content (Li & Ma, 2009; Li *et al*., 2010; Wu & Zhao, 2015) have significantly influenced wave attenuation. In these studies, the pressure bars were replaced with rock materials and the filled joints are modelled as sand/clay fillings at small thicknesses. The seismic wave is generated by the pendulum hammer or spring gun at lower wave frequencies and wave amplitudes. However, the response of fillings under realistic seismic waves contains (a) elastic compression of sand grains at lower loading stress, (b) slippage and rearrangement of grains at intermediate loading stress and (c) grain crushing at high loading stress (Whitman, 1980). This complicated deformation of the fillings makes the seismic attenuation across a fracture thickness dependent.

To simulate the dynamic response of fillings under seismic-scale impacts, the intact rocks are replaced with high-strength metallic bars and the particle crushing induced nonlinearity is revealed (Huang *et al*., 2016).

Manuscript received 9 March 2018; first decision 27 June 2018; accepted 9 July 2018.
Published online at www.geotechniqueletters.com on 27 July 2018.
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These nonlinear behaviours are influenced by initial joint thickness and in turn affecting the transmission character and seismic attenuation factor. To date, the effect of joint thickness on seismic response of sand-filled joint subject to high-amplitude seismic waves has received less attention. In practice, blasting stress waves are commonly much higher than seismic waves in amplitudes referring to field measurements (Singh, 2002; Khandelwal & Singh, 2007; Huang *et al*., 2016). This study is aimed to understand the effect of joint thickness on seismic wave attenuation across a filled joint at a thickness range from 5 to 15 mm. The seismic wave is simulated by a gas gun released impact at an amplitude more than 100 MPa and frequency as high as 1 kHz. The relationships between the joint thickness and loading/unloading initial stiffness, maximum closure, transmission coefficient, frequency as well as the seismic attenuation factor Q, are discussed.

EXPERIMENTAL SET-UP

Figure 1 shows the schematic diagram of the apparatus modelling P wave propagation across a sand-filled joint. The SHPB consists of a gas gun-loading apparatus, a wave propagation apparatus and a data-acquisition apparatus. The diameters of the striker, incident bar and transmitted bar are identical at a value of 50 mm. The 400 mm length striker launched from the gas gun generates a seismic wave having a wavelength of 800 mm and the maximum impact velocity as high as 40 m/s. The brass shaper having a diameter of 20 mm and 2 mm in thickness is adhered on the centre of the free end of the incident bar to generate a smooth rise of the stress wave to ensure stress equilibrium in the sample (Fig. 1(b)). Two strain gauges connected as a Wheatstone bridge are used to record the stress waves on the incident and transmitted bars. Three strain histories ε_{I}, $\varepsilon_{\mathrm{R}}(t), \varepsilon_{\mathrm{T}}(t)$, with subscripts I, R and T for the incident, reflected and transmitted waves were measured as functions of time t at a high sampling resolution up to 20 MHz. The incident wave and transmitted wave energies W_{I}, W_{T}, are performed to compute the seismic attenuation factor Q_{er} as follows

$$W_{\mathrm{I}} = \frac{A_{\mathrm{bar}} c_{\mathrm{bar}}}{E_{\mathrm{bar}}} \int \sigma_{\mathrm{I}}^2 \mathrm{d}t, \quad W_{\mathrm{T}} = \frac{A_{\mathrm{bar}} c_{\mathrm{bar}}}{E_{\mathrm{bar}}} \int \sigma_{\mathrm{T}}^2 \, \mathrm{d}t \tag{1}$$

$$\frac{1}{Q_{\mathrm{er}}} = \frac{\Delta e}{2\pi e} \tag{2}$$

where c_{bar}, A_{bar} and E_{bar} are the wave velocity, cross-section area and elastic modulus of the bars and σ_{I}, σ_{R}, σ_{T} are the stresses for the incident, reflected and transmitted bars, respectively. The seismic attenuation, Q_{er}, induced by the intrinsic attenuation and apparent attenuation is given by Knopoff (1964) and $\Delta e = W_{\mathrm{I}} - W_{\mathrm{T}}$ is the amount of energy dissipated per cycle excitation and e is the sum of the input energy which is equal to W_{I}.

The filled joint sandwiched in two bars is simulated by filled dry quartz sands at three thicknesses – that is 5, 10 and 15 mm. The quartz sands have a density of 2·5 g/cm^3, a mean particle size 1·3 mm (grain size range from 0·3 to 2·5 mm) and uniformity coefficient 1·64. During sample preparation, sand particles are filled into the confinement sleeve (50·2 mm in inner diameter) made of PMMA material to constrain the overflow of sands. As shown in Fig. 1(c), the sleeve has a thickness of 5 mm and length of 30 mm to decrease the lateral confinement. A small grease layer is filled in the mismatch between the bar and the sleeve to eliminate the unwanted friction effect (Li & Ma, 2009; Wu *et al*., 2013, 2014; Huang *et al*., 2016). The sands are loosely filled and the porosity of the joint sample is 33%. The density of the filling material is about 1·7 g/cm^3 in this study.

EXPERIMENTAL RESULTS

Figure 2 shows the stress waves measured on the incident and transmitted bars after different thickness filled joints. The amplitude stress ranges from 120 to 135 MPa and the

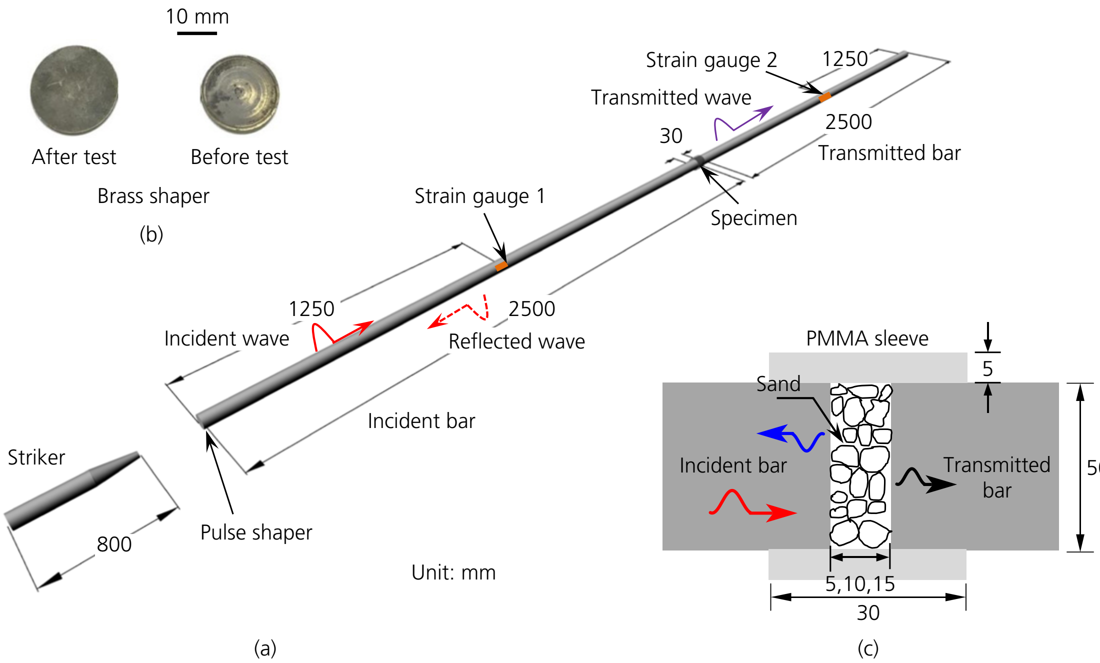

Fig. 1. (a) Schematic diagram of the SHPB apparatus for high-amplitude seismic wave propagation across a sand-filled joint, (b) brass pulse shaper and (c) sleeve configuration

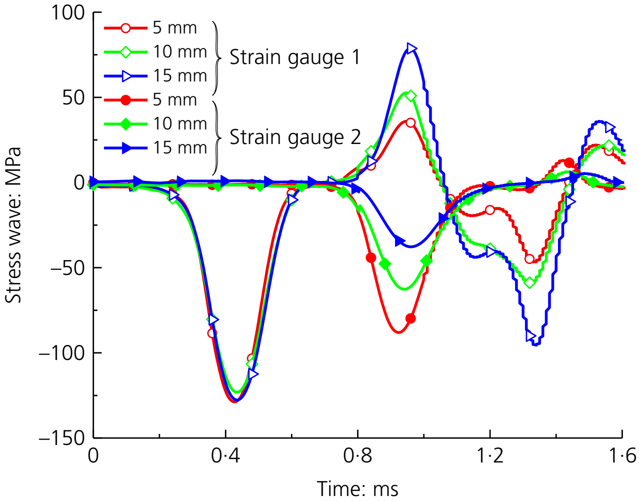

Fig. 2. Stress waves on the incident and transmitted bars at identical gas pressure for 5, 10 and 15 mm thickness filled joints

corresponding dominate frequency ranges from 0·98 to 1·23 kHz. The transmitted waves decrease as the joint thickness increases as shown in Fig. 2. The superposition of the reflected waves indicates that the wavelength has been enlarged after the wave across the fracture resulted from the filtering on high-frequency wave components. The dynamic stress–strain responses of the dry sand-filled joint at thickness of 5, 10 and 15 mm are shown in Fig. 3. The mechanical behaviour of sands are found to be nonlinearly deformed and the loading process contains a first compaction and then an elastic response. The typical relationship of the nonlinear joint is described as B-B model in the form of hyperbolic function. Apart from the nonlinearity of the loading process, the unloading behaviour has an influence on the wave attenuation with different initial stiffness and maximum closure. The dissipation resulted from particle crushing of the filling materials causes nonlinear hysteresis loop on the stress–strain relationship after loading and unloading processes. The change of nonlinearity of the unloading process is proved to have distinct influences on the energy transmission and transmitted waves (Fan & Wong, 2013; Ma *et al.*, 2013). Therefore, the piecewise

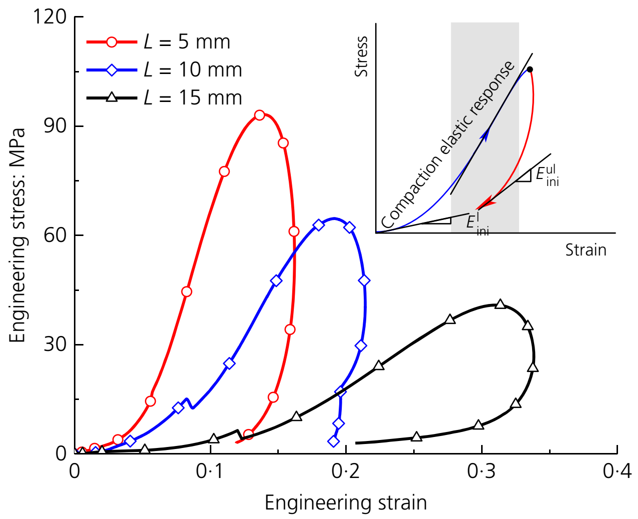

Fig. 3. Stress–strain response of dry sand fillings at 5, 10 and 15 mm thickness under dynamic loading

nonlinear model containing loading/unloading behaviour is defined as

$$\sigma^{(l,ul)} = \frac{E_{ini}^{(l,ul)}}{1-(L\varepsilon^{(l,ul)}/d_{max^{(l,ul)}})}\varepsilon^{(l,ul)} \tag{3}$$

where E_{ini} and d_{max} are the initial modulus and the maximum allowable closure of the joint. σ and ε are the normal stress and strain responded by the joint. The superscripts (l, ul) denote the loading and unloading processes, respectively. The influence of joint thickness on the initial stiffness and maximum allowable closure is shown in Fig. 4. The initial stiffness values of the sand fillings are 327, 146 and 50 MPa when the joint thicknesses are 5, 10 and 15 mm in the loading process. Similar results can be observed in the unloading process and the corresponding values are 239, 137 and 40 MPa. As expected, the thicker filled joint results in lower stiffness in loading/unloading process and eventually decreases the seismic transmission. Contrary results are presented for the maximum allowable closure. This closure increases from 1·2 to 7·2 mm when the joint thickness is increased from 5 to 15 mm in the loading process. This value decreases approximately 50% after the first compaction of the sands. For the granular sand-filled joint, the impact at high-stress amplitude compresses the sand layer, compacts the air-dry voids, rearranges the particle location and crushes the assembles. These behaviours increase the nonlinear deformation, enhance the stiffness and decrease the wave attenuation.

To characterise the wave transmission of the filled joint, the transmission coefficient T_p is defined as

$$T_p = \frac{\max|\sigma_T|}{\max|\sigma_I|} \tag{4}$$

Previous studies indicate the seismic attenuation Q as a function of depth (Harris *et al.*, 1997), frequency (Harris *et al.*, 1997) and saturation (Wu & Zhao, 2015). By taking the seismic attenuation as the ratio of the spectral amplitudes of the intact rock and fractured rock mass, the Q_{am} can be rewritten as a function of transmission coefficient

$$\frac{1}{Q_{am}} = \frac{1}{\pi}\ln\left(\frac{\max|\sigma_I|}{\max|\sigma_T|}\right) = \frac{1}{\pi}\ln\left(\frac{1}{T_p}\right) \tag{5}$$

Q_{am} is defined by maximum stresses in incident and transmitted waves. The transmission coefficient across a filled joint as a function of joint thickness is demonstrated in Fig. 5. At lower joint thickness, the high initial stiffness increases the seismic wave transmitted across the fracture. The presence of the discontinuities decreases the transmission of the seismic wave and this attenuation is approximately linear dependent on the joint thickness. Comparisons with thin-filled joints (2–8 mm thickness) under low-amplitude stress are presented and similar dependency on joint thickness of transmission coefficient is observed. The transmission is largely attenuated at the joint thickness 5 mm when the loaded stress is less than 10 MPa (Li *et al.*, 2010). This result is induced by the nonlinearity of the fillings under intensive loads. In general, the joint thickness affects the initial stiffness of the discontinuities and therefore the transmission behaves as thickness sensitive. On the contrary, the high-amplitude stress wave fully motivates the nonlinear deformability of the filled joint and in turn results in large transmission coefficient. The Fourier spectra after the fracture of different thicknesses are shown in Fig. 6. Apart from the attenuation on the amplitude, the joint generally causes frequency-dependent filtering on the incident wave. The filtering effect is also increased as the joint thickness increases.

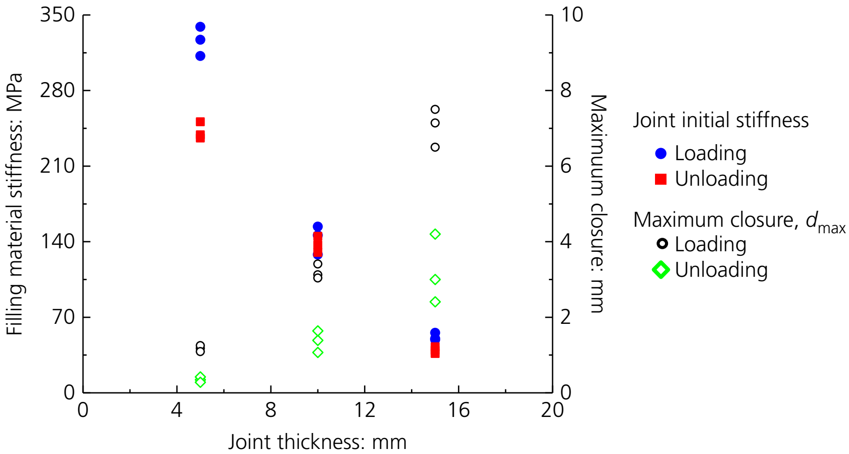

Fig. 4. Joint stiffness and maximum closure under loading/unloading processes at different joint thicknesses

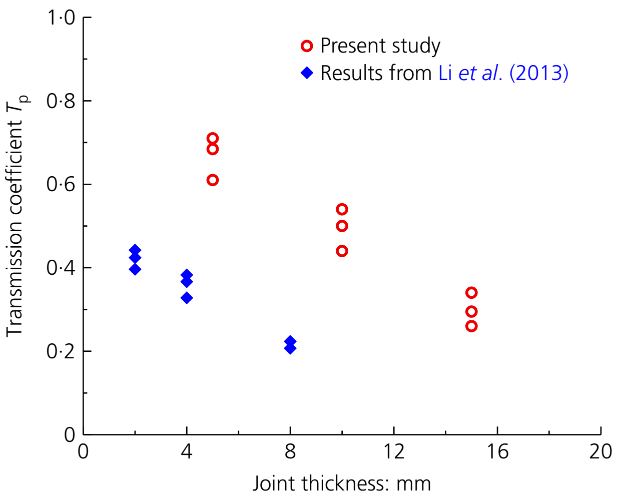

Fig. 5. Wave transmission coefficients as a function of joint thickness

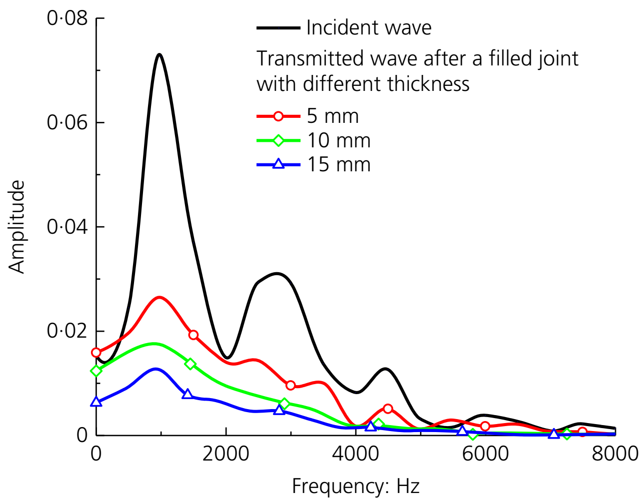

Fig. 6. Frequency spectrum of the incident wave and transmitted waves after different thickness joints

Figure 7 shows the change of seismic attenuation factor obtained by different variables as a function of the joint thickness. For the 5 mm thick filled joint, the seismic

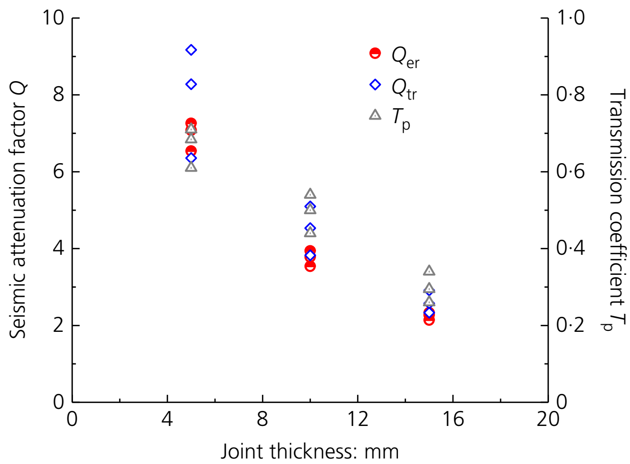

Fig. 7. Seismic attenuation factor as a function of joint thickness

attenuation factor derived from energy dissipation is 7·1 and that value obtained from wave amplitude (or transmission coefficient) is 8·8. Similar results can be observed for the joint thicknesses 10 and 15 mm. These results are caused by the fact that the transmission coefficient which derived from the amplitude of wave in time domain is not able to fully describe the frequency dispersion. Although the Q values derived by different physical variables present a similar decrease in the joint thickness as the transmission coefficient behaves, the physical mechanisms underlying the intrinsic attenuation are different.

CONCLUSION

The intensive seismic response of a fracture filled with dry sands at different thicknesses is experimentally studied using SHPB apparatus. Different with previous studies on filled joints, this paper aims to investigate the role of joint thickness with strong nonlinear deformability on the wave attenuation subject to intensive P wave incident. Loosely filled dry sands are used to simulate filled joints with three different thicknesses – that is 5, 10 and 15 mm. The loading/unloading processes in the form of B-B model are provided to describe the nonlinear behaviour of the filled joint.

The initial stiffness and maximum allowable closure are thickness dependent both in loading and unloading processes. The initial stiffness decreases with the joint thickness while the maximum closure has a contrary response. The transmission coefficient and seismic attenuation factor, Q, are studied from the view of energy dissipation. The thicker joint results in lower initial stiffness and in turn reduce the transmission coefficient. Moreover, the high-amplitude stress strengthens the nonlinearity of the filling materials and increases the stiffness in a similar way. The combined influence of the thickness and amplitude results in higher transmission coefficient for filled joint.

There are differences between the Q values obtained from energy dissipation and transmission coefficient. These results may be because the transmission coefficient, which focused on the amplitudes of stress wave in the time domain, does not fully consider the delay of phase velocity induced by frequency filtering. The seismic Q_{er} of the energy dissipation method is lower than that of the transmission coefficient method Q_{tr}.

ACKNOWLEDGEMENTS

This work was supported by National Natural Science Foundation of China (numbers 51439008 and 51679231) and China Scholarship Council (to the first author, number 201604910678).

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