Journal of the Mechanics and Physics of Solids 63 (2014) 40–50

Contents lists available at ScienceDirect

Journal of the Mechanics and Physics of Solids

journal homepage: www.elsevier.com/locate/jmps

The existence of a critical length scale in regularised friction

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ARTICLE INFO

Article history:
Received 6 March 2013
Received in revised form
4 October 2013
Accepted 6 October 2013
Available online 20 October 2013

Keywords:
Interface rupture
Regularised friction
Numerical modelling
Finite-element
Explicit dynamics

ABSTRACT

We study a regularisation of Coulomb's friction law on the propagation of local slip at an interface between a deformable and a rigid solid. This regularisation, which was proposed based on experimental observations, smooths the effect of a sudden jump in the contact pressure over a characteristic length scale. We apply it in numerical simulations in order to analyse its influence on the behaviour of local slip. We first show that mesh convergence in dynamic simulations is achieved without any numerical damping in the bulk and draw a convergence map with respect to the characteristic length of the friction regularisation. By varying this length scale on the example of a given slip event, we observe that there is a critical length below which the friction regularisation does not affect anymore the propagation of the interface rupture. A spectral analysis of the regularisation on a periodic variation of Coulomb's friction is conducted to confirm the existence of this critical length. The results indicate that if the characteristic length of the friction regularisation is smaller than the critical length, a slip event behaves as if it was governed by Coulomb's law. We therefore propose that there is a domain of influence of the friction regularisation depending on its characteristic length and on the frequency content of the local slip event. A byproduct of the analysis is related to the existence of a physical length scale characterising a given frictional interface. We establish that the experimental determination of this interface property may be achieved by experimentally monitoring slip pulses whose frequency content is rich enough.

1. Introduction

Understanding frictional interaction is crucial for studying complex mechanical systems. But it is challenging to gain more insights on friction by studying complex natural (tectonic plates, human joints, etc.) or engineering (gears, bearings, seals, etc.) systems. Thus, experimental research focuses on simplified systems with known properties and measurable behaviour. A wide range of experiments has been conducted on flat interfaces of a given pair of materials in order to analyse the fundamentals of friction (Baumberger et al., 2002; Ben-David et al., 2010; Maegawa et al., 2010; Rubinstein et al., 2004; Xia et al., 2004). These experiments revealed and analysed several phenomena: different propagation speeds of interface ruptures (from slow to super-shear) (Rubinstein et al., 2004; Xia et al., 2004; Ben-David et al., 2010), crack-like or pulse-like rupture (Coker et al., 2003; Baumberger et al., 2002), and precursor slip events occurring before global sliding (Rubinstein et al., 2004, 2007; Ben-David et al., 2010; Maegawa et al., 2010).

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0022-5096/$ - see front matter
http://dx.doi.org/10.1016/j.jmps.2013.10.007

Even though such experimental research gives additional opportunities to study phenomena occurring on more complex systems, they bear challenges as well. Accessing information at the interface, where an important part of the studied mechanisms happens, is difficult because the interface is hidden behind the bulk material. Experimental research often needs to rely on few measurement points distant from the interface, on transparent materials, and on a limited number of experiments. Therefore, numerical simulations are needed to confirm or complement the analysis of these mechanisms. Modelling local slip events at frictional interfaces between dissimilar materials (bi-material interfaces) using mass-spring models (Braun et al., 2009; Maegawa et al., 2010; Scheibert and Dysthe, 2010; Amundsen et al., 2012) or the finite-element method (Kammer et al., 2012; Di Bartolomeo et al., 2012) have shown many similarities with the experiments. However, these numerical models have an inherent problem as explained hereafter.

It was shown (Adams, 1995; Ranjith and Rice, 2001) that dynamic sliding of bi-material interfaces under Coulomb's friction law is in many cases unstable, which results in an unbounded increase of displacement oscillations in response to small perturbations at the interface. In real experiments such behaviour has never been observed. For the particular case of deformable-rigid interfaces, the stability of Coulomb friction was first studied analytically by Renardy (1992), and Martins and Simoes (1995). They showed that sliding of a linear elastic solid on a rigid surface is ill-posed if both the static and kinetic coefficients of friction are greater than one and equal. Moreover, if velocity weakening friction is applied, ill-posedness occurs for smaller friction coefficient as well.

In numerical simulations the instability due to the bi-material effect results in a lack of mesh convergence (Cochard and Rice, 2000). Therefore, most simulations of local slip events need some regularisation to solve this stability problem. Two strategies are known: either the regularisation is applied onto the bulk (*e.g.*, Rayleigh damping or visco-elastic constitutive material) or at the interface (*e.g.*, friction regularisation). In any case, however, it influences the dynamics of local slip events and thus raises questions about the interpretation of numerical results. The solution of interface regularisation is found in the results of experimental work by Prakash and Clifton (1993). They show that the frictional resistance does not change instantaneously to a sudden jump of the normal force, but evolves continuously with time. This observation opposes the Coulomb friction law $F=\mu N$, where the friction force F is proportional to the normal force N with the coefficient of friction μ. Recently, Kilgore et al. (2012) confirmed on a different experimental setup that there is no direct effect on the frictional strength due to a jump in the normal force. A friction law based on these observations introduces a length scale to the definition of the friction force. It was shown that the use of a simplified version of such friction laws renders the bi-material friction problem well-posed and allows to reach mesh convergence (Cochard and Rice, 2000; Ranjith and Rice, 2001). This regularisation of friction has since been used widely for earthquake simulations (Rubin and Ampuero, 2007; Kaneko et al., 2008; Brietzke et al., 2009).

In purpose of avoiding damping in the bulk, we assume here that friction is governed by the Prakash–Clifton law and focus our attention on its effect on the mechanics of slip at frictional interfaces. The parameters of this friction regularisation have important implications on the local as well as the global behaviour of friction (Di Bartolomeo et al., 2012), and need therefore to be chosen wisely in order to get meaningful numerical results. However, the choice of appropriate parameters is difficult due to the absence of experimental data for most materials. Furthermore, the characteristic length scale deduced from the experiments of Prakash and Clifton (1993) is of the order of micrometres (Cochard and Rice, 2000), which requires very fine discretisation and heavy computational efforts.

In this work, we study the rupture of interfaces between deformable and rigid solids governed by a regularised friction law. Equal static and kinetic friction coefficients that are smaller than one ensure a well-posed problem even without regularisation (Renardy, 1992). Choosing a slip event that is well-posed with and without a friction regularisation avoids a possible distortion of the analysis of the mechanics of regularised friction due to the transition from an ill-posed to a well-posed problem. In Section 3, we confirm that mesh-converged solutions are achieved without numerical damping in the bulk for sliding with regularised friction at a deformable-rigid interface. We then depict a convergence map with respect to the characteristic length of the friction regularisation and the discretisation of the interface. Using mesh-converged solutions, we show that the friction regularisation has for a given slip event a converging behaviour with respect to the characteristic length of the regularisation.[1] The behaviour of a slip event is the same for every characteristic length below the critical length. These observations are confirmed and explained in Section 4 by the high-frequency-filter effect of the Prakash–Clifton friction law. The implications of the converging regularisation are analysed in Section 5 showing that there is a domain of influence for the Prakash–Clifton friction regularisation linked with the characteristic length of the regularisation and the spectral content of the slip event. Outside this domain of influence, the propagation of a slip event under regularised friction is equivalent to the propagation under Coulomb's friction law.

2. Simulation setup

We study the propagation of a rupture at a frictional interface between a semi-infinite isotropic elastic half-space and a rigid flat surface (Fig. 1). This two-dimensional plane strain geometry as well as the material properties are similar to the systems studied by Andrews and Ben-Zion (1997) and Cochard and Rice (2000). We impose in x_1 direction Periodic Boundary

[1] Notice that throughout this article two different convergences are considered: convergence with respect to the mesh discretisation, and with respect to the characteristic length of the friction regularisation.