



High-amplitude elastic solitary wave propagation in 1-D granular chains with preconditioned beads: Experiments and theoretical analysis



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ABSTRACT

Elastic solitary waves resulting from Hertzian contact in one-dimensional (1-D) granular chains have demonstrated promising properties for wave tailoring such as amplitude-dependent wave speed and acoustic band gap zones. However, as load increases, plasticity or other material nonlinearities significantly affect the contact behavior between particles and hence alter the elastic solitary wave formation. This restricts the possible exploitation of solitary wave properties to relatively low load levels (up to a few hundred Newtons). In this work, a method, which we term preconditioning, based on contact pre-yielding is implemented to increase the contact force elastic limit of metallic beads in contact and consequently enhance the ability of 1-D granular chains to sustain high-amplitude elastic solitary waves. Theoretical analyses of single particle deformation and of wave propagation in a 1-D chain under different preconditioning levels are presented, while a complementary experimental setup was developed to demonstrate such behavior in practice. The experimental results show that 1-D granular chains with preconditioned beads can sustain high amplitude (up to several kN peak force) solitary waves. The solitary wave speed is affected by both the wave amplitude and the preconditioning level, while the wave spatial wavelength is still close to 5 times the preconditioned bead size. Comparison between the theoretical and experimental results shows that the current theory can capture the effect of preconditioning level on the solitary wave speed.

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1. Introduction

Elastic stress wave propagation in one-dimensional (1-D) granular chains has demonstrated novel characteristics stemming from the strong non-linear interaction behavior between granular particles in contact, i.e. the Hertzian contact (Nesterenko, 1983, 2001; Shukla et al., 1993; Zhu et al., 1997; Coste et al., 1997; Daraio et al., 2005, 2006; Jayaprakash et al., 2011; Awasthi et al., 2012; Pal et al., 2014). The non-linearity of the Hertzian contact response produces a new type of solitary wave with strongly non-linear features, quite different from weakly nonlinear solitary waves originating from the

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Korteweg–de Vries equation (Korteweg and de Vries, 1895). For example, in a 1-D granular chain, the spatial width of such a solitary wave does not depend on the loading duration while its wave speed has a nonlinear dependence on the loading amplitude. These features have been utilized to tailor the propagation of such strongly nonlinear solitary waves in specific microscale and macroscale designs to achieve desired goals such as pulse energy trapping and shock disintegration (Nesterenko et al., 1995; Coste et al., 1997; Molinari and Daraio, 2009; Ngo et al., 2012).

Because of the significant stress concentrations present at the contact region between granules, experiments can only have a limited maximum load level imposed by the need to maintain the elastic (Hertzian) nature of particle-to-particle contact. For example, the maximum load level for a contact point between brass alloy 260 beads with 10 mm diameter is about 5 N and between stainless steel 440 C beads with 25.4 mm diameter is about 500 N based on Hertzian contact theory and the von Mises yield criterion (Johnson, 1985). Any realistic dynamic loading application with substantial loading over the elastic limit such as blast or ballistic loading with a multiple kN loading level will cause plasticity, or other material nonlinearity, in the contact region. Since the appearance of plasticity significantly affects contact behavior between ductile particles (Li et al., 2009; Wang et al., 2013a,b; Pal et al., 2013), it also influences the formation of solitary waves. On et al. (2014) have shown the existence of a solitary-like elasto-plastic wave in a granular chain with ductile particles. This type of wave is different from the regular elastic solitary waves because of its diminishing amplitude, and the dynamics of the formation and propagation of such waves is not fully understood yet. In order to extend the applicability of the strong nonlinearity of solitary waves to much larger loading range, a granular system, which can retain elastic conditions under higher loading levels is necessary.

From the classic Hertzian contact theory, plasticity can be thought to initiate when the stress in the contacting body satisfies the von Mises yield criterion (Johnson, 1985). The elastic contact force limit (critical contact force for yield initiation) F_y is then given by

$$F_y = \frac{1}{6} \left(\frac{R^*}{E^*} \right)^2 (1.6\pi\sigma_y)^3, \quad (1)$$

where σ_y is the material yield strength. E^* and R^* are the equivalent Young's modulus and relative radius, respectively, defined as

$$\frac{1}{E^*} = \frac{(1-\nu_1^2)}{E_1} + \frac{(1-\nu_2^2)}{E_2}, \quad (2a)$$

$$\frac{1}{R^*} = \frac{1}{R_1} + \frac{1}{R_2}, \quad (2b)$$

where E is the Young's modulus, R is the radius, and subscripts 1 and 2 refer to the two different contacting particles. It is clear from Eq. (1) that if we want to increase the elastic contact force limit, we can either increase the contact radius (which is the same as the particle radius for spherical particles), decrease the Young's modulus or increase the yield strength of the material. Decreasing Young's modulus is neither easily achieved, since we can only choose from a limited set of existing materials, nor necessarily desirable based on static structural considerations. Therefore increasing contact radius and yield strength of the material simultaneously is the approach followed in this work.

Pre-yielding or strain hardening has been widely used for increasing the yield strength of ductile materials in application such as metal rolling or shot peening (Ray et al., 1994; Kim et al., 2008). Here we introduce a similar method, defined as preconditioning, in which an individual contact point is pre-yielded to a certain load level and then unloaded. Consequently, the contact point will remain elastic upon reloading as long as the load level remains below the original preconditioning amount. The goal of this work is to understand how preconditioning affects solitary wave propagation in 1-D granular chains and how to control the preconditioning process. We focus on three specific tasks: (i) Implementing the preconditioning treatment and quantitatively controlling the process; (ii) Experimentally and theoretically proving that the 1-D granular chain with preconditioned beads can sustain high amplitude elastic solitary waves; and (iii) Performing parametric studies to evaluate elastic solitary wave propagation in 1-D granular chains with preconditioned beads.

2. Theoretical considerations

2.1. Elasto-plastic contact behavior

In the present work, we only consider contact between identical spherical metallic particles that comprise a repeating unit in a granular chain and each contact point in the chain is preconditioned identically. A sketch of the contact force vs. displacement (between the centers of the two particles) for an identical spherical bead pair in contact is shown in Fig. 1a. Sketches of the contact point are also shown in the figure for three points during the contact loading and unloading process. The elastic region is represented by OA in Fig. 1a. When the load is increased beyond point A, plasticity sets in and is represented by the line AB. Since irreversible plastic deformation occurs in region AB, the unloading behavior follows a different path, line BC, which corresponds to elastic unloading.

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