Ascertaining Grain Scale Effects Of Seismic Or Aseismic Stimulation Upon Strength Of Near Surface Geological Materials

Bilal Hassan, Stephen D. Butt, Charles A. Hurich

Abstract: Certain peculiarities of inelastic nonlinearity of unconsolidated near surface periodically stressed granular media contributed at micro- scale are investigated to ascertain possible anomalous time dependent strength behavior macro-effects, with geotechnical/geo-environmental implications. Comparative examination of ultrasonic P- and S-wave repeatable displacement response wave-forms, in time records and spectra, of pulse stimulated both confined dry and fully saturated ceramic grains analogue, endorsable by pertinent theory, is performed. Examination is primarily aimed at both understanding connectivity of “louder” response generated by seemingly unobtrusive “quieter” seismic and aseismic events in granular sediments. Secondarily, results impart an enhanced conceptual substantiation of some previously disseminated and/or published results. The results hint certain persistive time and frequency restricted occurrences vouching vital insights. It could be unambiguously clarified that subtle acoustic emission and/or stick-slip type micro events in stimulated i.e., seismic or aseismic, unconsolidated granular sediments do occur. When spread over time and/or space their cumulated effect may be capable of altering granular material macro strength behavior. It is clearly deducible from resonant type spectral results that material fragmentation or force chain formation type phenomenon occurs possibly due to macro-scale friction mobilization by grain-scale events. It is further speculated that invisible high frequency events may irreversibly alter grain-scale surface properties and/or intergranular friction as (pseudo) enhanced elasticity type effect, more elusive with saturation. An assessment of an examined temporal distribution of grain-scale stick-slip type events when stimulated by P- and S-wave modes is posited to be non-identical. The former, as if, is retardation associated while the latter relaxation type, in a characteristic sense. Presented result forms combined not only offer acute insights in assessing possibilities of elastic wave mode conversion in granular sediments but also evolution of grain-scale effect to a macro-scale with potential of compromising strength and stability of unconsolidated sediments.

Index Terms: characterization of granular sediments, granular rheology and relaxation, granular media force chains, stimulated granular medium reorganization, P- and S-wave response of granular medium, unconsolidated sediments seismic/aseismic response

1 Introduction

Adequate knowledge and understanding of microscopic behaviour of unconsolidated and moderately consolidated dry granular media is scarce. Non-destructive evaluation (NDE) techniques/applications development of near surface including acoustics i.e., P- and S- waves, at macroscopic scales has brought certain microscopic phenomenon and associated atypical aspects to light, alongside. Their initiation mechanisms in scale are comparable to typical acoustic emission with possibility of occurrence or excitation of other converted modes. Collective effects of such phenomenon may introduce macroscopic granular material behaviour nonlinearity. Upon either an intensive or extensive stimulation, such localized occurrences assume capacity to create events which may change the overall rigidity and/or compressibility of surrounding media or sediments to resist deformation by disturbing the equilibrium/quasi-equilibrium either at repose or at a given state of memory. Intensive stimulation may include tectonic activity and associated or ensuing earthquakes or tremors.

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Most industrial and energy resource development activities/operations e.g., unconventional development, mitigation and sequestration/storage especially, tamper subsurface in discrete ways causing extensive stimulation. Patterned and peculiar repeated occurrence of these “acoustic” events in time and space affect a time dependent material behavior by irreversibly altering and/or impairing the strength of surrounding sediments or strata in a manner comparable to an episodic and/or seasonal reorganization. Such episodes either short term or long term may set off “unexpected” events of sizable geological scale eventually i.e., local to regional, such as landslides, slope failures, sink holes and avalanches, to mention a few, where the associated risks i.e., geotechnical and geo-environmental, posed to public and civic inhabitation and infrastructure are not difficult to ascertain. Adequate identification and description of the nature of emanation and magnitude of contribution of such microscopic scale phenomena/mechanisms holistically embodying material strength i.e., moduli, nonlinearities/ susceptibilities in NDE of unconsolidated near surface sediments for reliable inferring and interpretation is critical, hence. If the granular unconsolidated sediments partly or fully saturated are exposed to various degrees of physico chemical action of confined and/or mobile saturants, more exacting is the affair. In a relevant context few extended and complementing but conceptually self-contained results of previously reported porous-media-flow immiscible-displacement monitoring laboratory study are presented. Principal objective is renewing the import of enhanced characterization of the unconsolidated granular material in dry (air filled) state, when stimulated by ultrasonic P- and S-wave pulse transmission in a comparative sense, given above elucidation. Additional objective is to render more insightfulness to peculiarities of previously published results aimed at a spatio-temporal description of near subsurface hazardous fluid flow process morphology, in

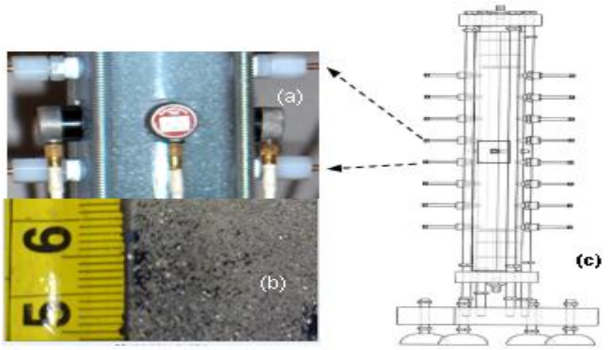

Fig.1. *(a) Measurement configuration of (dry) granular analogue, and (b) material size (0.5mm spherical ceramic spheres).(c) Granular analogue (45cm x 5cm) confined in the instrumented flow-cell with ultrasonic P- and S-wave source-receiver sensor pairs attached midspan.*

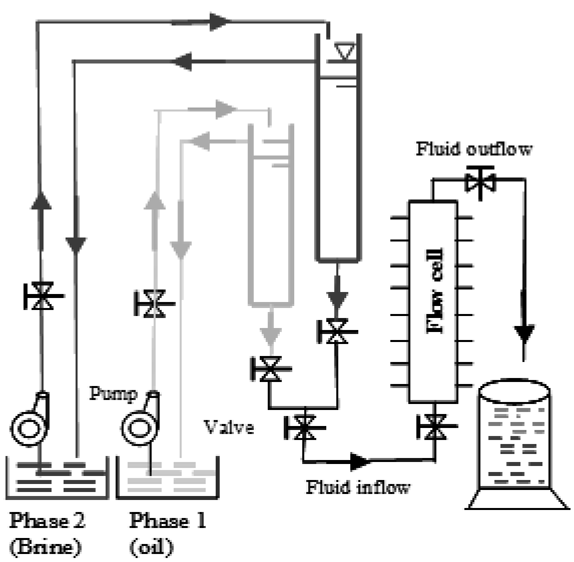

Fig.2. *Schematic of flow control system facilitated immiscible fluid-displacement process through the (saturated) granular analogue.*

Principle. Results are presented in graphical form, supported by pertinent theory and citations, for rendering sufficient plausibility and/or understanding of discussion given the objective, preceding the conclusions lastly. The interpretability of the presented results is naturally constrained, spatiotemporally, by the geometry of confinement of the investigated or probed analogue specimen. Panels of Fig.1a through Fig.1c with Fig.2 depict and describe both the size/scale and orientation of the unconsolidated granular material analogue, and the overall configuration of the experimental method, in relative sense. Fig. 1a shows the exact point or horizon of ultrasonic (pulsed) measurements or acquisition using 1MHz ultrasonic source-receiver sensor i.e., P- and S-wave, pairs. Fig. 1b is a close up photograph of the spherical ceramic beads or grains offering sense of size and shape of the single grains relative to the overall analogue when confined. Fig. 1c depicts the instrumentation of the confined analogue forming the flow-cell with broader details of design, where the exaggerated section of figure 1a is marked by a square. Fig. 2 is the schematic of the immiscible-displacement process, following dry measurements, showing the direction of fluids flow through the flow-cell apparatus confining the granular analogue, facilitated by a flow control system.

2 Theoretical Overview

Nonlinear variation in strain beyond the proportional limit for large stress, even periodic, at macroscopic scale is well understood. Nonlinearities may appear however, even assuming that infinitesimal strains affected by periodic force are fully recoverable. This deviation from Hooke's law suffers special significance, when considering/examining ultrasonically stimulated deformations/effects comparable to case at hand, especially. Numerical investigations of [1] show that such nonlinear effects may be quite "pronounced". Among these effects or nonlinear acoustic elements the clearly identifiable ones are acoustic harmonics, inelastic sound field interference i.e., Raman type scattering, and resonance. Detailed description of such elements of nonlinearity in terms of appropriate stress-strain/ wave propagation formulations considering direction/symmetries and thermodynamic/ conservative principles with consequent identification of higher order elastic moduli is provided too. Consequently thus the finite strains/deformations depend upon the physical properties of the deformed state or residual memory as opposed to the elastic nonlinearity where the effects are scaled by the original undeformed geometrical state only, clearly defining the geometrical and physical nonlinearity separately. Apart from macroscopic effects, microscopic type nonlinearities affected by crystal lattices or ordered internal structure present a more acute situation/challenge for possibilities of secondary excitations. Specific wave interaction scenario, including elastic, of plane waves traveling with same propagation direction is discussed as a particular case of propagation interaction. In polarization analysis context it is argued that one longitudinal and two transverse polarizations, mutually perpendicular, in superposition can represent any elastic wave in an isotropic solid. Such a synchronous nonlinear interaction of elastic waves creates several excitation possibilities where the amplitude of the generated wave increases in the interaction region. The transfer of energy from the interacting waves to the resultant wave of combination frequency occurs in such a way that the specific geometric conditions for synchrony of excitation of a wave frequency and wave vector under the influence of two plane waves are satisfied. The theory does not take absorption into account; however, clearly the absorption would only impose magnitude bounds on the amplitude of the resultant waves, as this material property is rendered immaterial to the phenomenon. The restriction of a monochromatic synchrony binds or follows optical transmission, it can be deemed permissible involving such evaluations, however, of sound or elastic transmission, with appreciation of the non-monochromaticity of transmission with associated deviations. Further, for such phenomenological characteristics, various applications of nonlinear acoustics are reasonably detailed by [2] with specific reference to NDE of granular geological materials; by using, among others, the ultrasonic attenuation, dissipation and dispersion based techniques. In characterization of granular media most important aspects are the notions of existence and control of static friction in bonds and contacts and dilatancy proposed by Coulomb and Reynolds in years 1773 and 1885 respectively, as of [3]. For idealized granular packs as usual analogues for granular media or typical sand pile models, effect/control of nature of contacts in terms of tractions/displacements in the presence of inter granular friction based adhesion or saturation when acoustically simulated i.e., P- or S-wave, several possibilities of the elastic wave propagation/polarization aspects including strength properties and/or moduli may arise. An understanding of such possibilities is provided in rigorous analytical wave propagation descriptions developed for several possible media/interfaces described in [4] and [5] including [6], [7] and [8] following, in essence, Hertz and Mindlin theory. Important aspect of a wavelength dependent time restricted /causal morphology of successive grain scale interfacial stick-slip occurrences is also identified. The elusive length scale dependent attribute of intergranular friction in acoustically stimulated granular medium is also examined and explained by [9] and [10]. Their experimental and numerical investigations suggest a possible micro to macro scale crossover as an isotropic behaviour to an anisotropic behaviour, due to a shift from wave like to diffusive mechanism of information transmission/wave propagation, which possibly affects a strength behaviour alteration. Manifestation of such alteration is enhanced elasticity by material reorganization or force chains formation. Aimed at understanding micro or grain scale behavior against periodic stimulation numerical and experimental investigations/ examinations of [11] and [12] involving 2D macro models of granular material have identified a rotational deformation/displacement field invisible beyond a crossover asymptotic dimension controlled by length scale i.e., number or elements or particles, coupled with global or translational steady state. They imply that an apparent mass associated rotational inertia with friction contributes at grain scale affecting the strength behavior. Their dynamic experimental evaluation of the morphology of rotation processes e.g. rolling vs. translational sliding combined effects, of plastic cylindrical elements as macro proxy of grains reveal a fragmented structure marked by stages or possibilities of “rotation” and “frustration” episodes as characteristic stick-slip model where frustrations may account for a friction controlled material

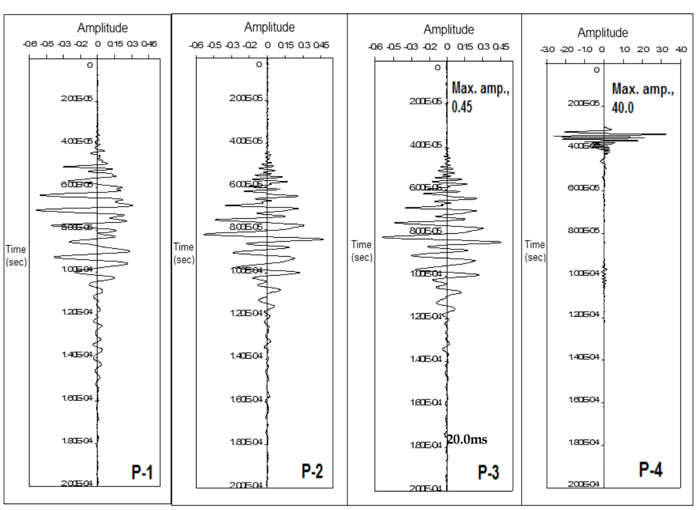

Fig.3. *Acquired, ultrasonic P-waves, P 1-3 dry and – 4 brine saturated.*

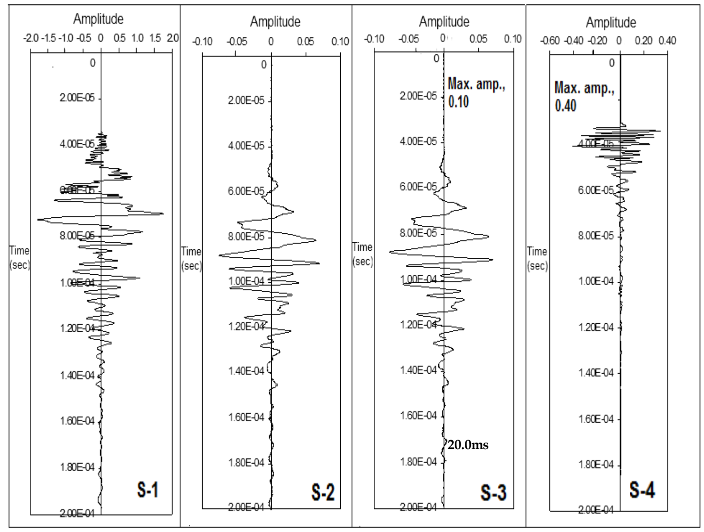

Fig.4. *Acquired, ultrasonic S-waves, S 1-3 dry and - 4 brine saturated.*

Reorganization. Assuming a hyperstatic contact conditions simulation with four different samples/numbers and distributions of circular disks/ particles were performed to evaluate the force distribution patterns [13]. The confined samples under zero gravity were vertically stressed with load of several tens of newton. They identified power law decay against an exponential decay in the forces lower and higher that their respective averages. This conforms to the plausibility of reorganization leading to force chain formation, implying that a sub-network with stiffer contacts bears more stress than that with compliant ones, controlled by a friction mobilization effect. In an experimental evaluation of force chains formation concept as percolation comparable phenomenon in compressed granular media, it has been found deformation acoustic distributed amplitude response also follows a power law, similar in sense [14].

3 DISCUSSION OF ILLUSTRATED RESULTS

Theoretical overview preambles the discussion of results to commensurate sufficiently, their presentation is so a sequence of several figure panels rather intentfully. It offers brevity and imparts their causavity, similitude, and correlation in a self-explanatory sense either examined isolated or mutually compared. The 20 ms traces in panels of Fig. 3 marked P1-P4 and those of Fig. 4 as S1-S4 represent P- and S-wave. Panels P4 and S4 of Fig. 3 and Fig. 4 are measurements of brine saturated medium, while panels P1-P3 and S1-S3 represent dry measurements, respectively. Fig. 5a and 5b depict the intrinsic transmitted P- and S-wave pulse (spectral) characteristics, for a benchmark. Among Fig. 6a through Fig. 6c, Fig6a and Fig. 6b represent measured/received rather examined spectral response of P- and S-wave dry measurements, given information of Fig. 5a and Fig. 5b, correspondingly. Fig. 6e shows P- and S-wave dry and brine saturated velocity estimates consistent with spectral results reported in [15] and others cited and referred to there in. Given Fig. 3 and Fig. 4, it is noticeable in “characteristic” sense that P-wave transmitted displacement amplitudes are significantly higher in magnitude compared to those of S-wave in dry medium. S-wave response to saturation effects, however, in temporal pattern and magnitude of displacement amplitudes, and velocity is significant compared to those of P-wave in proportion. This clearly implies an altered granular material elasticity controlled by propagation characteristics and saturation effects combined. Apart from deduction of consequent changes in rigidity and compressibility manifested in velocity estimates presented in Fig. 6c, the causative mechanisms could be inferred by comparative examination of “temporal variations character” of time domain signals/traces of corresponding P and S panels. In mechanistic sense the elastic energy transmission in saturated medium occurs in a short single/distinct wave like pulse for both ultrasonic P- and S-waves i.e., P4 and S4, in dry medium however character of transmission signature appears to be series or sequence of well separated or delayed instances in time, each representing a discrete state. Further two groups, a “faster” or less time separated low amplitude followed by a “slower” one with greater time separation high amplitude steep instances/occurrences could be observed for each of P1-P3 traces, with trend being opposite in S1-S3 traces. A very interesting observation is that “faster” instances/amplitude events contain repeated sub-occurrences as magnitude fluctuations with a little to a without “zero –crossing” in all of P1-P3 and S1-S3 traces. It could be both deduced and posited that a material fragmentation is observed and/or caused due

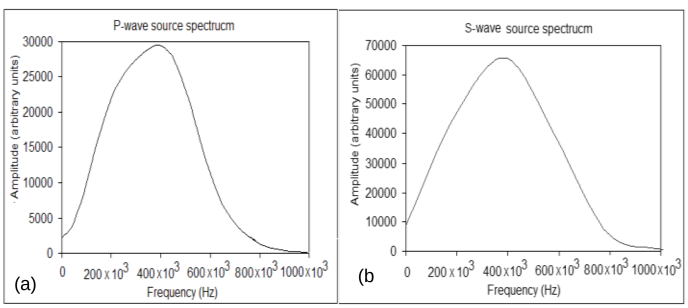

Fig.5.*(a) P-wave, and (b) S-wave transmitted spectral characteristics.*

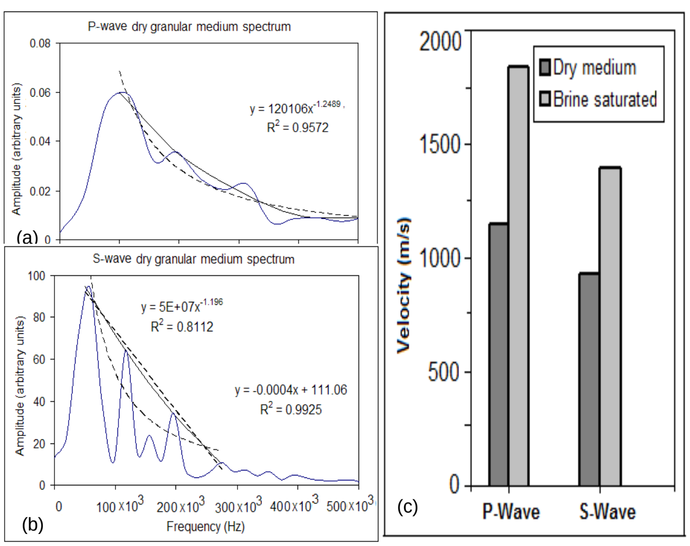

Fig.6. *(a) P-wave, and (b) S-wave received (measurement) spectral characteristics. (c) Velocity estimates corresponding to Fig.3 and Fig.4.*

To a granular reorganization affecting elastic properties during ultrasonic energy transmission. The reorganization is possible consequence of high frequency content of transmitted band in case of P-wave transmission and comparatively low frequency one in case of S-wave transmission where localized stick-slip events may occur as hardening events in P-wave transmission as opposed to energy decay events in S-wave transmission owing to polarization aspects/effects related stick-slip phase issues. The fragmentation reorganization could be unambiguously confirmed from resonance type P- and S-wave spectral effects, more pronounced in case of S-wave propagation, as shown in Fig. 6a and Fig. 6b respectively. The notion of elements of nonlinearities manifested specially as resonance type spectral effects for an elastically stimulated viscoelastic response behavior can sensibly grasped by consideration and/or comparative examination of mechanical and electrical analogue components, while assuming air as non-zero viscosity saturant of the granular analogue. The occurrence of consequent antiresonance and resonance frequencies both for retardation and relaxation (stimulated) conditions with corresponding amplitudes are rendered more appreciable, thus. Material characterization on the basis of such spectral evaluations is more realistic especially where macro- and micromechanical material behavior may assume inhomogeneity and anisotropy. Usefulness of such “corresponding” mechanical and electrical analogues could be understood from [16] and [17] given the posited dynamic stimulated or transmitted P- and S-wave polarizations and responses. Amplitudes clearly decay from lower to higher frequencies as a power law, specific to the case.

4 Conclusive Remarks

Seemingly quiescent periodic seismic and aseismic macro events are capable of tampering the unconsolidated near surface dry material strength at micro scale to cause unexpected accelerated or “louder” events. Micro behavior examination, as much warranted to understand and address civic risks, under ultrasonic stimulation shows that intergranular friction controlled acoustic emission and/or stick-slip type events may constitute or embody a macro material reorganization, where their morphological nature against P- and S-wave stimulation is different in a purely characteristic sense. High frequency occurrences and/or transmission appear capable of irreversibly altering grain scale surface and/or friction properties as an enhanced elasticity effect. It may cause/generate unexpected response contrary to convention especially in case of S-wave transmission under saturated conditions. With peculiar nonlinearities manifested as spectral resonances, dry unconsolidated granular material behavior appears significantly different from quasi-linear effective medium type that of saturated one, requiring caution and an understanding of length scales for any acoustic stimulation based geotechnical and geo-environmental inferring.

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