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Viability assessment of integrated P- and S-wave surveys using ultrasound

Bilal Hassan[a]
[a]*Memorial University of Newfoundland, St. John's, Canada*

Abstract. Potential of, integrated geophysical, especially P- and S-wave combined near surface surveys, is assessed; demonstrated with use of sparingly, reduced chronographic i. e., time and velocity, (1 MHz) ultrasonic imaged data. Case of aqueous and non-aqueous, predominantly, fossil fuel origins spills seepage within near-surface geology is examined in terms of evaluation of possible complexities of fluids and surrounding interactions; which are experimentally simulated embodied as flow components of an immiscible displacement process. Such processes are understood and studied widely, within various, especially near-field geo- and engineering including environmental and also geo-disaster contexts. Interesting relevant scenarios, including aspects, of geological complexity of well known geographical locations while their subjugation also to various, whether natural or anthropogenic, stressors are presented alongside pertinent theory for better grasp, including plausibility, of methodology and inferring. Experimental analogues and geometrical constraints are explained in detail. Ultrasonic P- and S-wave, data in relevant context, also verified analytically, are comprehensively evaluated. S-wave data not only corroborates P-wave data attributes in time-space localization of displaced, from displacing phase, including a "dim spot", an interesting artifact corresponding to interface (or mixed phase) region, S-wave also manifested other elastic and thermo-mechanical characteristics of the same feature. Further a flow rate, especially, that of injection, control or dependence of a planned displacement process was confirmed, for example if required in tracer and remedial studies. S-waves characteristic suitability to reveal other fluid-fluid and fluid-solid interaction peculiarities at micro and possibly at nano scale, as amplitude effects, is foreseen to assume significant promise.

Keywords: integrated geophysical mapping, combined near surface surveys, P- and S-wave integration, ultrasonic characterization

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ГЕОЛОГИЯ, ПОИСКИ И РАЗВЕДКА МЕСТОРОЖДЕНИЙ ПОЛЕЗНЫХ ИСКОПАЕМЫХ

Научная статья
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Оценка эффективности интегрированных исследований продольных и поперечных волн с помощью ультразвука

Билал Хассан[a]
[a]*Мемориальный университет Ньюфаундленда, г. Сент-Джонс, Канада*

Резюме. В статье оценивается потенциал комплексной геофизической, в частности комбинированной приповерхностной, съемки продольных (P-) и поперечных (S-) волн, что продемонстрировано с использованием умеренно сокращенных хронографических (время и скорость) данных ультразвукового изображения (1 МГц). Рассмотрен случай инфильтрации разливов водного и неводного происхождения, особое внимание уделено разливам ископаемого топлива. Последние оценены в пределах приповерхностной геологии с точки зрения возможных сложностей взаимодействия жидкостей и окружающей среды, которые экспериментально моделируются в виде компонентов потока несмешивающегося вытеснения. Такие процессы широко изучаются в различных областях, в частности при геозондировании становлением поля в ближней зоне, инженерии, включая экологические аспекты, а также геокатастрофы. Для лучшего понимания проблемы наряду с соответствующей теорией, достоверной методологией и выводами в статье представлены интересные актуальные сценарии, в том числе вопросы геологической сложности хорошо известных географических мест, влияние на них различных естественных или антропогенных стрессовых факторов. Подробно объясняются экспериментальные аналоги и геометрические ограничения. Ультразвуковые P- и S-волны и аналитически проверенные данные в актуальном контексте получают всестороннюю оценку. Данные об S-волнах не только подтверждают набор признаков данных P-волны в пространственно-временной локализации смещенной фазы, включая «тусклое пятно» (что является интересным признаком, соответствующим границе раздела (смешанная фаза)), S-волны также проявляют другие упругие и термомеханические характеристики того же свойства. Далее автором был подтвержден расход, в частности расход нагнетания, а также контроль или зависимость запланированного процесса вытеснения, например в маркерных и коррекционных исследованиях (при необходимости). Предполагается, что пригодность характеристики S-волн для выявления других особенностей взаимодействия систем «жидкость – жидкость» и «жидкость – твердое тело» в микро- и, возможно, в наномасштабе (например, амплитудные эффекты) будет иметь значительные перспективы.

Ключевые слова: комплексное геофизическое картирование, комбинированные приповерхностные съемки, интеграция продольных и поперечных волн (P-волн и S-волн), ультразвуковая характеристика

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Introductory background and motivation

Monitoring of the Earth's surface and near subsurface is essential for understanding several geo-and dynamic processes. Non-destructive applications offer efficient and economic methods to achieve this goal, and interest especially in such applications is much renewed due to need for better understanding of or exploring geo- and environmental degradation and other disasters linkage to climactic changes among other situations of concern, especially in real time. A noticeable and well known cause of many environmental problems of near surface are light aqueous and non-aqueous subsurface flows due to fluid spills and incidental releases i. e., industrial strong brines and light hydrocarbons, resulting at times in complex and sediment degrading fluid fronts and interfaces while acting as solvents too.

Such occurrences are not uncommon in urban development when various kinds of industrial material products, especially by-product and / or waste, for example as in mining, and oil and gas transportation, are inappropriately handled or disposed. The immediate hazard associated with such events is usually of thermo-chemical nature. The situation however may evolve and worsen if the hazard effect may be compounded when such saturants not only pose risk of soil and water contamination, but may alter the geo-mechanical and morphological characteristics of, especially immediate, surrounding sediment through physico-chemical interaction. The characterization and remediation of such flows usually explicable by porous-media problems becomes even more challenging when the contaminated sediments, already a complex environment, are further exposed to other disasters either as (i) natural and / or (ii) anthropogenic events, such as water events of rains and floods, earthquakes and aseismic effects of industrial activity.

Such interactions may induce ground deformation as abrupt ground movement or creep sufficient enough in magnitude to instigate local subsidence or sliding and erosion effecting civil infrastructure integrity, on one hand, alongside also affecting and extending overall environmental contamination and pollution foot-print and stressing further of restorative economics, on the other. Sediments with fluid contaminant percolation, thus, either exposed to different extrinsic anthropogenic and meteorological natural events effects, or prejudiced by the complex intrinsic predisposition for pre-existing geologic stressors, hazard associated with porous flows of toxic releases and flows due to either type of, usually connected, cases is quite complicated with both physical and chemical dimensions. Reliable characterization for appraisals, on sound technical grounds, of the overall risk is equally challenging. Efficient and reliable monitoring and forecasting for realizing robust procedures of containment and mitigation of such flows and associated hazards, especially when several levels of ensuring safety (i. e., operational, procedural) fail to curtail frequent occurrence, or consequences, of such hazardous incidents, appear as indispensable.

For a more interested reader relation and connectedness between natural agents and forces constituting complex regional geology in long time scales, and those associated with short time scale seasonality of seismic / geologic, climactic and weather, including aseismic and other anthropogenic, events simultaneously acting towards effecting and altering subsurface sediment's strength and integrity is understandable from, a suitable, example, regarding some above said effects of Italian geology and subsurface. Only brought to attention for historical significance, and out of personal interest, Italian geology at all continental, regional and local scales could be considered well fitting real life situation of complex geo-system, also well studied and recorded as both geo- and enviro-stressed at different time scales. Italian geology for it's genesis towards existing constitution, owes for most part, in nature to the same regional processes consistent with the morphing of the geology of the Mediterranean region, marked particularly with, spatial, occurrence and recurrence of significant local geological events at different time-scales and spans. These agents, namely, historically also well studied, in terms of a time-magnitude scale are of the nature of continental rifting, tectonic dynamics, subduction with regeneration, folding and mountain building, faulting and seismic actions or earthquakes and consequences, as of [1] and [2], meaning also that consequent geological system can persistently not be characteristically tabular and flat, and further not dormant or stagnant but active. Aside from contribution of purely regional level generative, morphing and reproductive agents and / or aspects, there could be non-regional or relatively local events affecting geo-system complexity. They can further transform a geological system and hence also the corresponding geophysical signature acquired, compared to the regional background. For most part such agents constitute meteorological events as rains, stream flows and floods with impacts especially of recurrence and seasonality in conjunction. Such local events with existing prevalent influence of anthropogenic (or anthropic) activities related to urbanization, agriculture, civic and industrialization directly or indirectly appear to control surface morphology and geohydrology, while effecting also the subsurface saturant's mode both of occurrence and existence, and in composition concentration and pathways / pattern of their flow. They, in short, influence the so called near surface as various actions too, as identified by [3] and [4].

Industrialization driven anthropogenic effects (also defined as anthropocene effects) upon near surface, in addition and combination with natural effects, could create significant geo-environmental impacts unnoticeably, long term. For example, examining the exemplified situation of Italy further, industrial activities with population increase from 1950 through 1980 affected, a variety of native geology and geo-morphology by creating a complex of geo-environmental problems in near surface. In this regard Po valley had been especially and significantly affected, polluted, as reported mostly for inorganic chemicals and radicals contamination of subsurface. Adverse groundwater contamination associated geo-mechanical affects had been reported in the case of central and southern Italy, characterized by local sliding and subsidence, assisted by excessive ground water abstraction [5]. Further, ground water contamination and flows controlled by cyclical seawater intrusion events as being a cause of ground or land deformation or movement of shallow subsurface is also identified by [6].

In addition to issues of purely geological and geotechnical nature, as highlighted through an arbitrary example that of Italy, the concern also over extended geo-environmental foot print of almost existential nature, with specific reference to ground water quality, has dramatically risen globally. Opposed to emergency type responses, emphasis on appropriate policy development and procedures for establishing long term solutions / capabilities invites attention. In this regard availability of quality water referred to as a direct collective development indicator for the next and rest of this millennium clearly and alone signifies the need to attain efficient and reliable capabilities for near surface monitoring of hazardous flows and ambient sediment / strata and aquifers for conservation, preservation and restoration[1] [7]. Several examples of such occurrences in North Americas both on land and sea could be cited and explored but are considered beyond scope, since the discussion largely in essence has been kept as conceptual extension of subject matter and analyses in[2]; however recent initiatives and interests could be reviewed from[3,4], and further a broader and simpler grasp of major and relevant geo- and environmental processes of concern could be sought from [8–11].

The overall, to this point clarified, and understandably, potential of the hazard associated with near surface saturants and releases is contingent upon their possible mode of existence and / or occurrence whether confined or mobile and also upon concentration and volumes, so it comprises both of qualitative and the quantitative effects. Among qualitative, predominantly physico-chemical and time dependent effects of geotechnical consequences or nature may cause triggering of failure of any dormant, seemingly stable, structure and feature or bedrock. Aspects of such effects upon sediments could be understood from [12].

Non-invasive geophysical mapping for monitoring of the subsurface as a method is well understood and established for technical feasibility. It since vouches capability of inescapably capturing influences of a complex geological ambience due particularly to possibilities and consequent effects of anthropocene activity of industrialization, consumption and affluence within expanding metropolitan habitat and housing. The seemingly reliable non-invasive mapping, however, becomes ironically challenging and elusive if the applied technique is unable to unambiguously resolve and map the subsurface object and target or process of interest, with all constituent elements, despite detectability. Mapping of subsurface, since, given the crux of subsequent discussion too, refers not only to identifying and delineating all physical features of interest related both to an anomalous structure and that of existence of contained or entrapped fluids or solvents given uniform background geology but also towards gaining further insight. It includes information about dynamic behavior of structure under external stimuli such as, exemplified hitherto, especially external stresses of mechanistic origins and any changes in flow either in pathways or regime and flow components in chemical constituents or fluid-structure morphology i. e., fluid fronts or boundaries and interfaces etc., in relevance to overall fate, respectively. Measurement or extraction of accurate geophysical data attributes and patterns and their space-time correspondence to underlying anomalies is central, in gaining a geological description sense, and to also arrive at a structural understanding where specific patterns i. e., images, are anticipated to directly confirm size, orientation and geometry of the flows types and paths, or conversely and additionally offer an improved lithologic understanding to infer whether a single phase or multiphase subsurface flow would be detected, with other possible details of constituents.

To summarize, the objective is to present findings of a laboratory scale non-destructive process evaluation and imaging study and examine the integration of geophysical data to assess viability of combined P- and S-wave surveys in near surface. The motivation on theoretical side is drawn upon need for monitoring and containment of oil and brine spills and releases related to petroleum or hydrocarbon production processes. The process of interest simulated, to recall, was an immiscible-displacement for it's applicability

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[1] Water is a pre-requisite for all development: World Water Council position paper on water and the Post-2015 framework. *Worldwatercouncil.org*. Available from: https://www.worldwatercouncil.org/sites/default/files/events/2013_10_09_Budapest_Water_Summit/WWC_Position_Paper_on_water_and_SDGs_Final.pdf [Accessed 24th December 2021].

[2] Citation removed as of initial review policy.

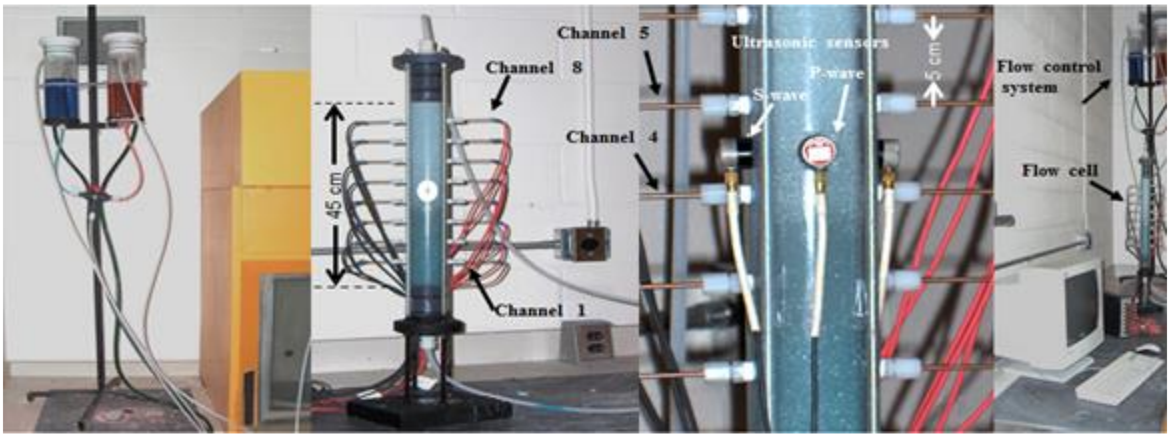
[3] Contaminated sediment remediation. Guidance for hazardous waste sites. *Semspub.epa.gov*. Available from: https://semspub.epa.gov/work/HQ/174471.pdf [Accessed 24th December 2021].

[4] Managing contaminated sediments. *Serdp-estcp.org*. Available from: https://www.serdp-estcp.org/Program-Areas/Environmental-Restoration/Contaminated-Sediments [Accessed 24th December 2021].

not only to several aspects of geo-energy systems but also to much beguiling deformable porous-media-flows macro and micro-scale implications in several realms especially geo-environment. The integrated methods approach in such circumstances is envisioned to be viable, since stimulation and / or energization in two different ways i. e., polarizations, phenomenologically measures (a) different sets of properties over the same or comparable spatio-temporal domain and (b) provides reliable and abundant information compared to that of even individual data sets combined acquired at different times in statistical terms and may help infer (c) aspects which would be difficult to grasp in individual observations of different and multiple data. Such integrated arrangements, with existing technologies as evolving and becoming less expensive, are achievable without significant extra efforts / costs incurred compared to the value of anticipated outcomes. Challenging possibilities of integrated geophysical near-surface monitoring applications and techniques for the future, as they are ever evolving and expanding, are being concurrently tested and put into practice. Broader and detailed relevant accounts, for further reading, of such possibilities and implications, applicable at different scales, could be sought from [13], and also [14, 15], and references therein.

Apparatus and method

The experimental simulation exercise, in a geological concept sense, would also imitate such occurrences as complex of near surface caused due to incidental fluid release or infiltration of aqueous and non-aqueous solvents. Three, in this regard, full scale integrated non-destructive measurements, disregarding dry runs and other experimental tuning, led to acquisition of substantial amount of data. Experimental tuning involved standard (velocity) measurements with water, different rock samples and empty (core) tube given performance / statistical characteristics of sensors to determine and confirm adequacy of received signal strength and realistic picking of wave-form first arrival travel times, as analog pre-amplification before digitization was also employed to improve acquired signal. The results offered an adequate detectability and reliability for all examined data. Significant correlatable similitude since was observed in achieving distinct spatio-temporal localization of pure phases or saturations of (i) oil and (ii) brine, and importantly (iii) an interface or a mixed-zone with associated fluid fronts was also unambiguously identified against the background matrix. The physical simulation exercise as it involved displacement of oil by brine the global flow was controlled and developed directed vertically against gravity through a porous unconsolidated medium / sediment analogue at fully saturated constant head conditions, i. e., Darcy regime. Two main apparatus components were designed to be used to facilitate and realize different types of data acquired essentially as integrated. One piece of apparatus consisted of an instrumented vertical transparent PVC tube with 5.09 cm inner diameter circular section i. e., a flow-cell system, to house and confine sediment core, connectable to the second piece of apparatus, a flow control system for saturating the flow cell analogue and especially maintaining invading fluid flow rate at constant head conditions. Pictures of laboratory arrangement of the apparatus components to enable understand the functioning of the two components with underlying concept are shown in Fig. 1. The analogue for unconsolidated sediment core was 0.5 mm spherical soda lime glass bead-pack (or granular pack) confined inside the flow-cell in 45 cm long section of transparent tube oriented and secured vertically. For acquiring ultrasonic data, 1 MHz P- and S-wave, source-receiver diametrically mirroring sensor pairs, were positioned mid-span flow-cell orthogonally, respectively, at flat machined seats to establish perfect contact for through (pulse) transmission. The arrangement allowed an adequate sampling or measurements for maintaining a reasonable spatial and temporal resolution during imaging of the fluid-displacement for any pre-selected invading fluid flow rate. The flow-control system was externally powered by a 1.5 hp centrifugal pump to keep fluid vessels remain filled. A regulated fluid flow through the granular sediment analogue within the flow cell against gravity was ensured with control valves provided at the top and bottom end pieces of flow-cell system and with allowance for raising and lowering of the fluid containing vessels of flow control system along the vertical holding stand.



a *b* *c* *d*

Fig. 1. Laboratory arrangement of the apparatus components:
a – constant-head flow control system showing oil phase and brine phase reservoirs with different dyes for visual discrimination in an initial test; b – flow cell system containing or forming the granular core (instrumented) analogue firmly held with tension rods anchored on a fixed aluminum pedestal with adjustable damping or isolating feet (not shown); c – close up snapshot of 1 MHz source receiver sensor pairs in through transmission configuration; d – flow control system and flow cell system connected to data acquisition system imitating bench top immiscible fluid displacement arrangement

Рис. 1. Организация компонентов оборудования в лаборатории:
а – система управления постоянным напором, демонстрирующая резервуары с нефтяной и соляной фазами, окрашенные разными красителями для визуального отличия в начальном опыте; b – система проточной кюветы, содержащая или образующая аналог гранулированного сердечника (оснащенного контрольно-измерительной аппаратурой), прочно удерживаемого натяжными стержнями, закрепленными на неподвижной алюминиевой опоре с регулируемыми демпфирующими или изолирующими ножками (не показаны); c – снимок крупным планом расположенных парами датчиков «источник – приемник» с частотой 1 МГц в конфигурации сквозной передачи; d – система управления напором и система проточной кюветы, подключенные к системе сбора данных, имитирующие устройство вытеснения несмешивающихся жидкостей

The overall physical with procedural arrangement enabled predetermining reasonable initial flow rate/s controlled at constant head conditions to allow sufficient amount of time, given the length of sediment analogue section and sensor positions, for all possible phases, flow types and / or morphologies (i. e., pure fractions and interface evolution), of interest to fully developed before being imaged. End pieces secured and aligned with steel tension rods in place restrained, as shown, the sediment analogue in the flow cell tube as they were held in sufficient tension to also allow structural stability while stressing and compaction of the granular / bead material for achieving sufficiently stiff grain to grain contact and keeping the flow-cell tube mechanically isolated and relaxed. Tension rods were anchored to an aluminum tetra pod pedestal or base-plate, 19.5 × 15.5 × 4 cm in dimensions, with leveling screws at each corner to allow perfect leveling, stability and damper footing pads (not shown) to reduce effects of ambient noise in acquired signals. A flow disc seated or rested next to and covered 1cm round center bore hole of each end piece inserted in place at bottom and top of flow cell tube, while secured between the granular material and end piece insert. On each of them were provided grooved and perforated flow channels designed as radiating from the center of, and towards, perimeter (circular) while covered by a mesh. Flow-disc as for its design, and mesh covered, would act as a granular material retainer, and also ensure steady uniformly distributed inflow or outflow of fluids without shock effects. Two continuous circular sealing rings about 3.75 cm apart provided at the middle of the 9 cm long end piece shaft or insert would be pressed between the outer surface of end piece insert and interior of the tube to allow a unidirectional flow only and keep the end-piece appropriately oriented in place. The developmental and adaptation aspects of the ultrasonic data acquisition system for various applications can be sought in [16] and [17] with other references therein. Three experiments with different initial / invading flow rates, explained further, with preplanned control, were considered adequate for analyses, alongside others performed as base line measurements, as indicated. Developing transparent reservoir / core analogues or apparatus arrangements in concept assists in visual examination for attaining better tuning and calibration. Use of such apparatus for examining fluid phases or fluid flow processes for laboratory experiments, in historical context, could be understood reported by [18] and [19].

Theory of controls and mode of integrated measurements

In this section the aggregate of ceramic beads or grains forming the analogue of unconsolidated sediment core is discussed in a phenomenological sense based on some known and established theoretical conventions or considerations. Further including also the geometrical and topological aspects these considerations are imperative in assessing physical properties, in addition to characteristic behavior, for experimental design as at hand. It is also understood and assumed held that both the (a) space and (b) time restricted, say displacement, velocity and acceleration associated responses are translated towards acquired measurements or signals. Amongst them meaningful signal attributes can be inferred as self-descriptive images for determination of an existing state, while examine either individually or combined, which otherwise would be onerous to be determined analytically. In this regard, aspects or possibilities of intergranular contacts, nature of internal forces and packing effects in dry and saturated state, in response to an external stimulation sense are elucidated, and only seminal works are afforded upon discretion.

Apparent Parametric Constraints for Granular Packing. Certain ssituations such as unconsolidated land and ocean porous sediments and comparable materials can be conveniently considered analogous to or depictable by an assemblage of grains or beads. These sediments further could also, while being subjected to or in interaction with localized external forces of nature and similar agencies, in response behavior considered as comparable to a confined static pack as if undergoing a shaking caused repeated packing type organization (and / or re-organization) of constituent elements. Assessments of their behavior are bounded naturally by aspects of granular size range including distribution (if not uniformly identical), contacts types in geometry and magnitude of area and their variability, contribution of granular surface properties including friction, and local and global fluid saturation and flow effects are also important factors or considerable restrictions of granular material or sediments dynamic description. Further there also is a well observable possibility of an affectation, as hinted, characteristic of an evolution and / or self-organization of granular background medium upon measurements and interpretation, given topology and restricting geometry.

A constant and statistically isotropic, for the case under consideration, porosity of 26 percent for the granular pack considering the number of contacts according to [20] is constantly maintained. The collective elastic (or ultrasonic) response for 0.5 mm spherical soda lime beads is assumed so to be consistent with mechanics of regular arrays and discrete particles following [21]. In addition are also considered and / or brought to attention propositions of [22], including those of [23, 24] and also works [25–28] in similar context. The elastic response for 0.5 mm spherical soda lime spherical beads assemblage or pack is assumed, to be also explicable following well known Hertz and Mindlin theories, sufficiently adequate for a satisfactory description of overall oscillatory / dynamic behavior, i. e., velocities, amplitudes and other characteristic possibilities. Kepler conjecture as of [29], and further bounds defined by [30] for packed isolated spheres, without any points of contact being (theoretical restriction of size change) coincidently common, is assumed held. Furthermore all grains are assumed equal spheres, as with no dimensional overlap, falling within the possibility of forming a cubic and / or a hexagonal random closed packing with sufficient and / or relevant maximum number of contacts. The possibilities of nature of contact forces experienced by granular sample array upon external stimulation, given types of contacts, are illustrated in Fig. 2 and Fig. 3. Acoustic scattering and geometrical / spatial diffraction since might create, other, subtle but significant effects as brought to attention by [31] and [32] in such materials / situations. Effects of diffraction in elastic wave propagation through saturated porous media are discussed in detail by [33] and [34], to understand the phenomenon.

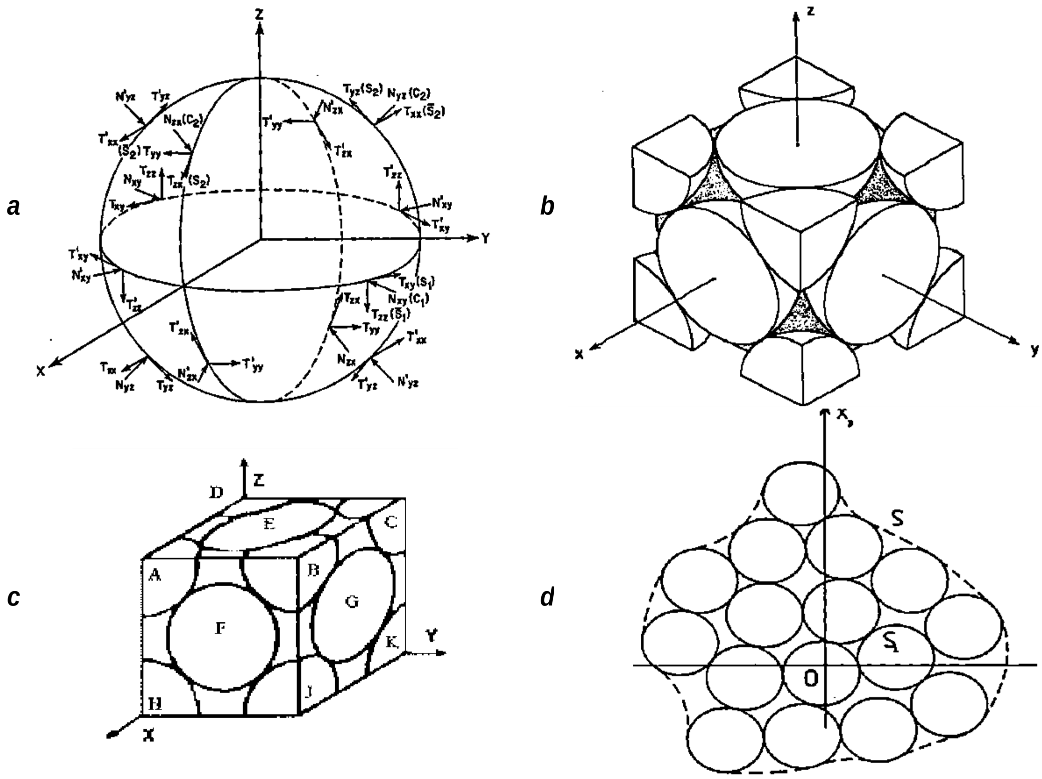
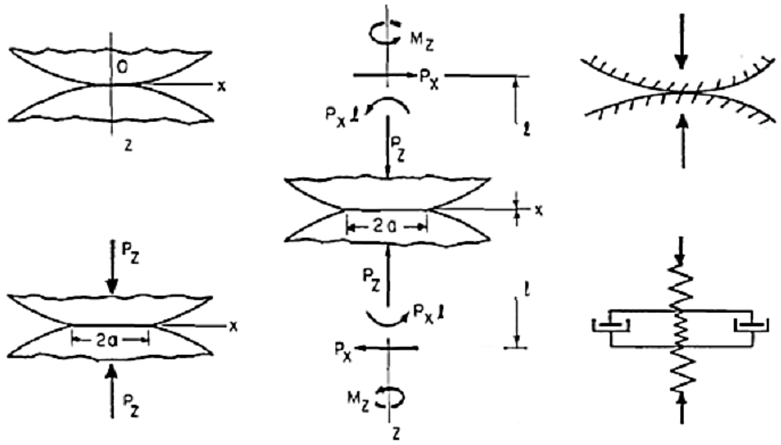


Fig. 2. Possibilities of forces acting on a single grain surface, and within a representative equivalent volume:
a – direction of various contact forces acting upon a typical spherical grain [23]; b – arrangement of spheres in a face-centered cube [22]; c – element of volume of face-centered cubic array of spheres; d – a random set of spheres within a large number bounded by a surface under stress [24]

Рис. 2. Возможности сил, воздействующих на поверхность одного зерна и действующих внутри представительного эквивалентного объема:
a – направление различных контактных сил, действующих на типичное сферическое зерно [23]; b – расположение сфер в гранецентрированном кубе [22]; c – элемент объема гранецентрированного кубического массива сфер; d – случайный набор большого количества сфер, ограниченный напряженной поверхностью [24]



a b c

Fig. 3. Nature of contact forces experienced by granular sample array upon external stimulation:
a – nature of granular contact unstressed free and under normal force; b – intergranular contact under pressure [22]; c – granular contact in presence of saturant represented with a rheological model [25]

Рис. 3. Характер контактных сил, действующих на массив гранулированных образцов при внешнем воздействии:
а – характер ненапряженного зернистого контакта и контакта под действием нормальной силы; b – межгранулярный контакт под давлением [22]; c – зернистый контакт в присутствии насыщающего агента, представленного реологической моделью [25]

This implies that ray theory holds in acoustic arrival time and velocity estimates. However, when analyzing the amplitudes or energy variations, diffraction effect and its consequences may dictate or merit observations beyond spatio-temporal localization / description of object or phenomenon of interest additionally.

Other salient delimiting aspects would be the geometry of space of confinement, degree of confinement, quantity, size, and arrangement of the granular constituents i. e., grains or beads, especially in ray path, effecting and contributing to the static component of the observations. For any unique investigative method applied to, especially non-destructive, and / or energies propagated through the process of interest and inferred reliably, understanding of restrictions of illumination of the targets and / or that of method itself holds importance. For example in through transmission of ultrasonic energy, non- and contact coupling options are available usually, with different arrangements of application. For the type of experimental arrangement, static and fixed or grounded, both gel and permanent glue couplants types were tested to determine and understand the bearing of nature of coupling on the morphology of acquired signals in terms of consistency, adequacy and quality. Permanent glue type adhesive was chosen and used as couplant between sensor and flow-cell finished surface offering a firm contact an uninterrupted continuous acquisition for several hours in any given experiment.

Surface Tension and Fluid Micro Structure Aspects. Liquid droplets, when exposed to atmosphere tend to acquire a particular shape, and this behavior is controlled by the physical properties of a given liquid. Water drops for example are uninfluenced by gravity effects at times as they do not collapse, and flow and spread on a surface i. e., non wetting. They appear to contract themselves to attain a minimum surface area, as close possibly as to a sphere. The reason for this physical behavior is that surface molecules, of a body of liquid, are not as much affected by intermolecular cohesion as those towards the inner part of the volume, for instance as in the case of water. The restriction of attaining the minimum energy of equilibrium results not only in formation of minimum surface area but causes surface molecules hold tightly together, spontaneously, as if in tension. This phenomenon is called surface tension, as well known. Surface tension is defined usually as forming of an interface by liquid surface exposed to or in a “contact” with atmosphere (atmospheric conditions) only, shown in Fig. 4. When both phases are liquids however, understanding of an interface happens to be different by definition. When water, again for example, is placed in direct contact with oil, the contact interface formed would have a contractile tendency. Contractility implies acquiring a minimum area with a definite molecular arrangement and orientation given their (chemical) properties and type. Orientation specifically of dipolar nature of molecules occurs at an interface when, as a specific example, the hydroxyl group, say, of an alcohol molecules would immerse in water to form and interfacial layer. The interfacial layer between two fluids is at times termed, or rather could be a, monolayer. Free surface of a liquid fluid, so, could in behavior be deducibly understood as layer with tensile or elastic properties. Physical existence of such elastic stress is difficult to realize, since, the dimensional restrictions, though well constrained, of mathematical formulation, does not clearly, support and allow convenient grasp. Existence of such interfaces is reported to persist (without ready dissolution or diffusion) even while undergoing deformation and is argued to occur by an energy equilibration caused due to a mutual exchange or cross-transfer of low and high energy molecules from free (i. e., Helmohltz free energy) surface and bulk volume energy of fluid, concurrently, with the meanings of providing for a chemical potential balance. Such propositions and possibilities are depicted in Fig. 5. Further such equilibration to occur could be understood considering the kinetic molecular theoretic. Fluid bulk phase could be considered at rest while molecules in an agitated state of motion assume several possibilities of effecting entropy given when interfacial molecules have a different liquid in property or state on either side the monolayer.

Total surface energy is considered greater than the free surface energy on grounds and definition that it is excess of the potential energy possessed by the number of molecules within the bulk phase when compared to same number of molecules forming a surface. Arguments point

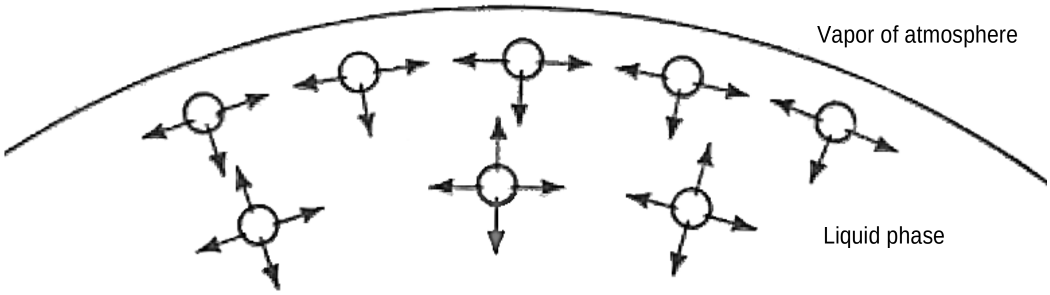


Fig. 4. Surface tension phenomenon depicted with possibilities of intermolecular forces and their orientation [35]
Рис. 4. Явление поверхностного натяжения, возможности межмолекулярных сил и их ориентация [35]

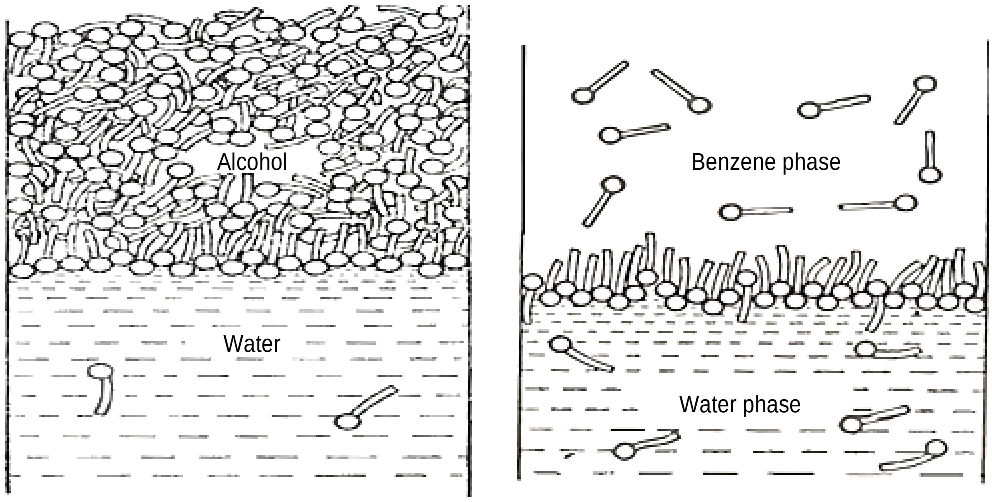


Fig. 5. Depiction of interfacial monolayer formation with molecular orientation and possibilities of motion for electrochemical equilibration for two water based bulk immiscible systems modified [35]
Рис. 5. Изображение формирования межфазного монослоя с молекулярной ориентацией и возможностями движения для достижения электрохимического равновесия для двух объемных модифицированных несмешивающихся систем на водной основе [35]

to a unit basis of dimensionalities of Helmohltz free energy definition. Adding to the above, monolayer is also propositioned to have strength properties, both of compressive and shear strength, indirectly confirming to assume elasticity. Compressive and shear strength properties have usual meanings, however shear strength is understood as capability of withstanding the torsional effort, as if, by concentric circular layers. Two very important consequences of these properties are that monolayers including immiscible interfaces have capacity to retain structure and significant wave damping capacities. It is clearly understood that both fluid molecular concentration in type (density effect) and the surface lubrication aspect (viscosity effect) should cause observable wave (thermodynamic) damping. Reported findings of other studies however suggest that it is difficult to ascertain which parameter may control or is responsible for maximum damping. Viscosity appears to affect a drag type effect too in monolayers formation and deformation, and further a direction and frequency dependence of any stimulated-wave damping is deducible, given manner and implications of measurement methods.

On each side of the interfacial immiscible monolayer different liquids should occur, and the molecules of those liquids would have tendency to be attracted to each other, both like and unlike molecules. Cohesion defines the force of attraction between like molecules while adhesion is that between unlike molecules. If the force of attraction between unlike molecules surpasses that of like molecules, it introduces miscibility, as surface energy is naturally minimized further. A work of adhesion is defined as the force per unit area required to overcome the cohesion, where work of cohesion with similar conceptual meanings and dimensions for a single liquid is twice as much as its surface tension, as two propositions are slightly different. In energy terms thus complete miscibility occurs when work of cohesion approaches a minimum. A conceptual mechanism of exchange of work for miscibility is shown in Fig. 6 where a stable, and agitated or moving mixing oil-water “immiscible” interfaces are shown side by side. Such energy exchange is speculated to occur by local or eddy flows within global flow involving momentum exchange. For specific and clear appreciation of wettability and affinity of different phases of an immiscible process or system, contact angle is the primary, if not the only parameter.

A simple pictorial definition or concept of contact angle is shown in Fig. 7. The variability in contact angle is an indirect measure of degree of variability between cohesion and adhesion. Changes of cohesion and adhesion since determine degree of miscibility or immiscibility, and consequently effects of saturant mobility given material property variation restriction of the energy variation, for conservative principles. Wettability has a greater significance in case of a three phase system, for example, where solid phase is also involved, and several parameters and their interaction in a complicated manner affect the consistency of the solution or mixed phase. Most of discussion in this section follows, excerpts and concepts from [35] alongside several pictures for relevant illustration. Other references therein are not explicitly cited and explained for brevity.

Aspects of Global Fluid flow. In experimental simulation, under consideration, conceptually a light non-aqueous phase liquid or oil fully saturating sediment is being displaced by brine against gravity, in each of a set of three experiments, to recall. Given, so, the manner of fluid confinement in the sediment analogue, the identical parameters of physical and chemical nature of the two different fluids, the invading and invaded phases, naturally happen to be significantly apart in magnitudes. Such a choice also facilitates better observation and clear appreciation of their effects on the acquired data, especially when inferring requiring a comparative analysis. The gravity, since, of oil phase when pure and / or free bulk state is 0.761 with viscosity of about 10 cp compared to gravity of brine being 1.03, which with the salinity of 3.5 % simulates sea water with assumed viscosity of 1.3 cp, to be able to create an inviscid flow. It thus could be speculated that

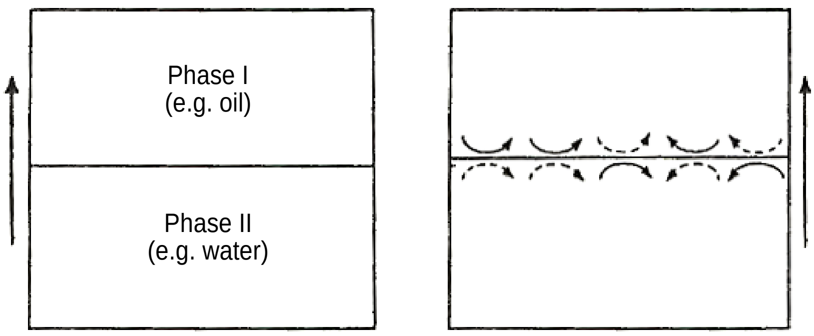
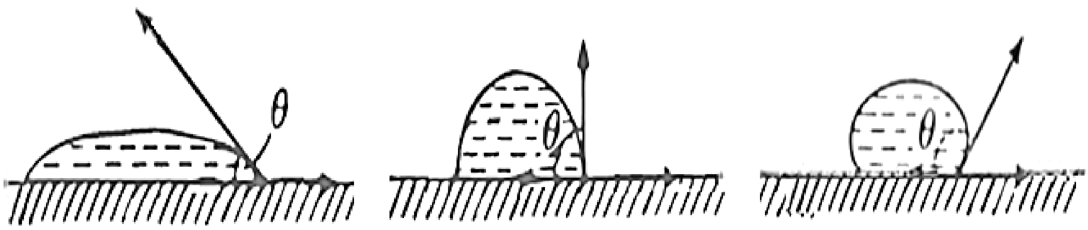


Fig. 6. A stable and unstable immiscible bulk oil-waver interface [35]

Рис. 6. Стабильная и нестабильная несмешивающиеся границы раздела нефтепродуктов и волны [35]



a ***b*** ***c***

Fig. 7. Contact angle “θ” as a measure wetting by spreading of a fluid on solid surface:
a – low contact angle showing preferential wetting comparable to hydrophilic in an aqueous case; b – a higher contact angle showing less spreading; c – very high contact angle depicts fluid phobia as in hydrophobia modified [35]

Рис. 7. Краевой угол θ как мера смачивания при растекании жидкости по твердой поверхности:
a – небольшой краевой угол смачивания, демонстрирующий преимущественное смачивание, сравнимое с гидрофильным в водном растворе; b – больший краевой угол смачивания, свидетельствующий о меньшем растекании; c – очень большой краевой угол смачивания, указывающий на фобию жидкости, подобную модифицированной гидрофобии [35]

effects of variability of parameters should be vividly significant, as proportionate effect of viscosity difference i. e., about 75 %, is much pronounced compared to that of density difference apparently, for type of porous / granular confinement, interestingly.

For the physical realization, of immiscible displacement process, the invaded or the "displaced" fluid phase of the process was introduced first into the unconsolidated core analogue of granular pack for attaining complete saturation. It was ensured or confirmed that the saturation was hundred percent and spatially uniform as air was also vacuumed out if required to eliminate any effects of air, bubbles or partial saturation. For creating or choosing the initial flow rates of the displacing or invading fluid phase, to start with, nature of flows similar to that of subsurface were considered, and kept in the broader perspective, to achieve only create realistic flow initiation and an overall morphological imitation, discussed further below. An adequate understanding of the nature of such subsurface flows and measurements assumed being consistent with different subsurface processes can be sought and inferred from work of [36–40]. The flow rates of choice, were, 0.044, 0.11 and 0.64 ml/s corresponding to values of about 4, 10 and 55 L/d defining or identifying a slow, intermediate and a fast flow rate experiment correspondingly. Categorically stated, the chosen flow rate variation range was to or would not only to a large extent fall within the limit or explicable both of soil-seepage type and observed at reservoir scale, or flows measured / observed in near surface aquifer characterization, but would allow reasonable number of measurements taken also well resolved in space-time sense, and anticipated to offer a plausible inferring. P- and S-wave data were simultaneously acquired and it was ensured that any individual single instance of measurement would be recorded by both the P- and S-wave sensors almost at same instant, representing same physical event confirmable also by time stamps of the measurement instances.

Discussion of results

Relative positioning of P- and S-wave source and receiver pairs, connected mid-span of flowcell length, shown in Fig. 1, *b* and Fig. 1, *c*, clarifies the manner of acquisition, organization and structuring of the (digitized) data given the geometrical arrangement. It further should enable the reader understand the graphical illustrations presented in the rest of figures. Data, to remind, are organized arbitrarily, however systematically, while taking into consideration and, to enable, an understanding of time delays of successive measurements, alongside organization with summation, done to offer advantage of a 2-D spatio-temporal effect from single point measurements, exploiting and also manifesting the inherent usefulness of experimental design.

Further the method of presentation ensures ready comprehensibility of any individual graphical result (and resultant) in significance, and additionally maintains and preserves the mutual relevance of individual figures of different outcomes in terms continuity of instances or measurements of interest in space-time. Consequently, a reduced contrived or manipulated cross-section of data are presented for complete unambiguous understanding of whole from part. Fig. 8, *a* thus, spontaneously, informs about how several measurements acquired as a sequence in time be presented sequenced in space to create an image of a single point monitored process. In Fig. 8, *a*, so, waveforms of Time 1, Time 2 and Time 3 are single point measurements separated in an elapsed time sense, where each measurement or observation within itself is a dynamic and causal signal. It is clearly observable that three signals or waveforms, that of Time 1, Time 2 and Time 3 depict an arrival time delay and amplitude variations with elapsed time. Signal of Time1 corresponds to oil saturation measurement, Time 3 signal corresponds to brine saturation measurement, both intense in amplitude, and deducibly signal of Time 2 is associated with the mixed phase zone, less intense or dim in amplitude. If not proportionately juxtaposed, and / or examined separately the three measurements would inconspicuously appear alike, hence justification of several of above comments in the discussion hitherto regarding nature of data presentation method applied and that of measurements.

Temporal anatomy of typical P-wave signal compared to S-wave signal for a brine saturated medium is shown, examinable, in Fig. 8, *b* against Fig. 8, *c* respectively within 2.0 ms equal duration.

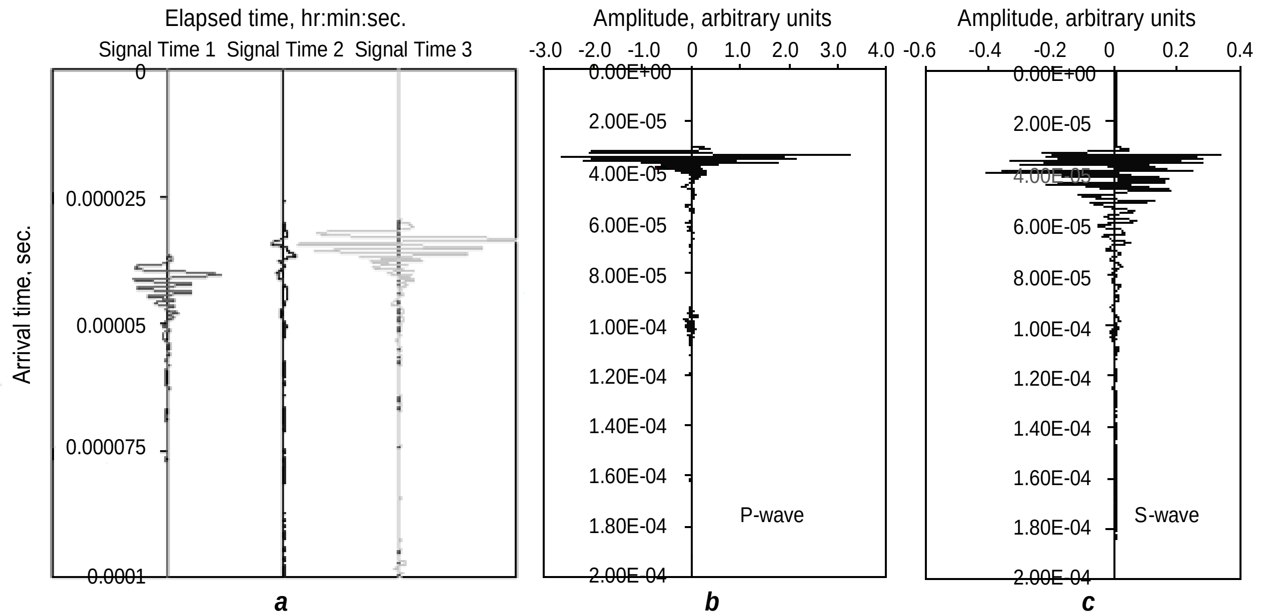


Fig. 8. Times of single point measurements:
a – an example of acquired data structuring to form an image of the process; signals of Time 1, Time 2 and Time 3 are single point measurements separated in an elapsed time sense, where each measurement is dynamic and causal (delays so in arrival time and amplitude variation are also visible); b – anatomy of typical P-wave signal compared to (c); c – S-wave signal for a brine saturated medium within 2 ms equal duration

Рис. 8. Время точечных измерений:
a – пример структурирования полученных данных для формирования образа процесса; сигналы Время 1, Время 2 и Время 3 представляют собой точечные измерения, разделенные по признаку истекшего времени, где каждое измерение является динамическим и причинно обусловленным (также заметны задержки во времени вступления волны и колебания амплитуды); b – структура типичного сигнала P-волны по сравнению с (c); c – сигнал S-волны для насыщенной рассолом среды в течение 2 мс равной длительности

The difference in the character of signals, as presented, is unambiguously identifiable to discriminate between P- and S-wave measurements. In terms of facilitating detailed examination for inferring, Fig. 8 contents provide two pieces of useful information. Firstly P- and S-waves signals as measurements are reliably “discriminate” and secondly both types of measurements would, and further should, undergo an “arrival-time and amplitude” change respective of and consistent with (i) energy type i. e., compression or shear, and (ii) nature of displacement variations, respectively, i. e., a definite pattern. Such wave-forms constitute chronographs or time-sections, with observably persistent patterns in a distinct and characteristic manner to create “images” descriptive, and allowing the plausible inferring, of morphology of the immiscible displacement process. Fig. 9 is a “close up” and shows pure S-wave mode while identifiable from associated converted P-wave mode, in an experimental verification sense, for reliable S-wave velocities determination and analyses. P-wave mode is usually observed along S-wave mode, mostly in significantly low but varying intensity. The occurrence is a constant static feature due to the sensing element configuration and working design, while intensity may depend upon, method and scale of survey and configuration. It can sometimes cause challenge in a legitimate S-wave data discrimination and even acquisition if sensor and / or receiver is not understood and deployed properly or sensor configuration or properties are altered, especially in case of low signal to noise ratio case measurements. The received signals since were recorded, and also transmitted by using same type P-wave and S-wave sensor pairs and were discreet; the recorded data were so phenomenologically accurate and truly representative of the events of interest and any irrelevant interference would naturally be filtered out.

Data as of manner presented in Fig. 8, *a*, allows forming or computing ultrasonogram “images” especially suitable for juxtapositioning and comparisons of individual measurements such as shown in Fig. 10, allowing identification of legitimate anomalies and features, standing out. Important aspects such as arrival time and amplitude

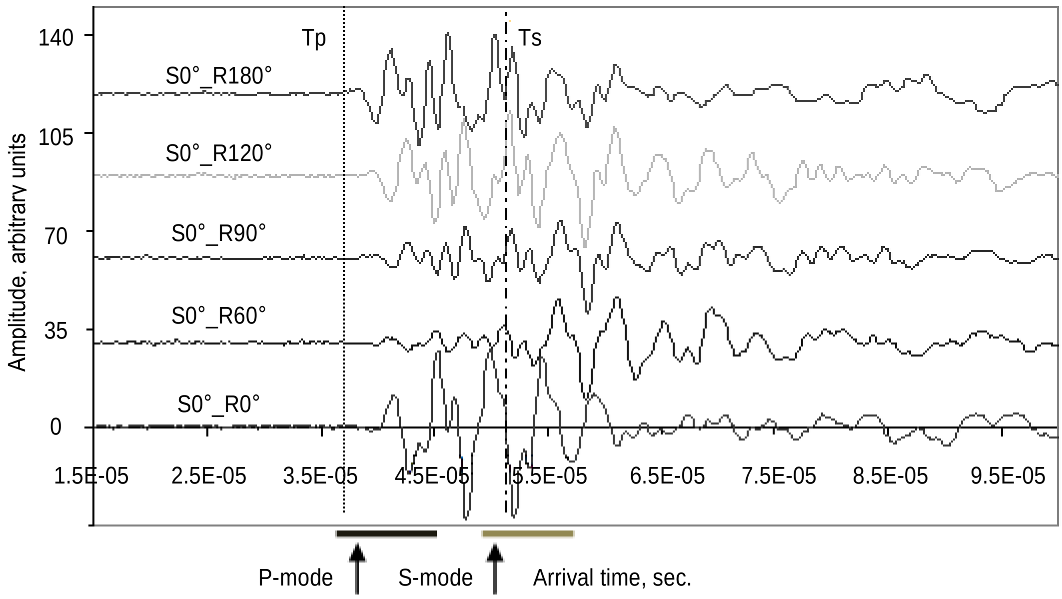


Fig. 9. Demonstration of isolation of P-wave and S-wave modes for time irrespective windowing for detailed analyses

Measurements made by stepwise rotation the receiver R relative to fixed source S. Note that for P-wave significant first arrival events only change in amplitude but not in polarity, while S-wave events are delayed and undergo both amplitude and polarity shift with some phase effects

Рис. 9. Демонстрация изоляции типов колебаний P- и S-волн методом независимого от времени окна для подробного анализа

Измерения производятся путем пошагового вращения приемника R относительно неподвижного источника S. Важно заметить, что значимое событие первого вступления P-волны характеризуется только изменением амплитуды, но не полярности, в то время как события S-волны задерживаются и претерпевают сдвиги как по амплитуде, так и по полярности, сопровождающиеся некоторыми фазовыми эффектами

anomalies for example of Fig. 10 are more visibly identifiable for more focused analyses if needed. Each trace or signal shown in any panels of Fig. 10 is time stamped to verify and examine either an independent measurement while also allow follow the progress of the process of interest from corresponding measurement sets or events against elapsed time. In Fig. 10, besides, more distinct anomalies of arrival times and amplitude variations occurrence of a “dim spot” anomaly at elapsed time of 50 min, 5 min and 1 hr instants during Test 1, Test 3 and Test 2 respectively is especially significant.

It is observable that occurrence of relatively low amplitude artifacts before the “dim spot” are different in character from relatively high amplitude artifacts following it. It is conveniently deducible that the former correspond to the flow of the invaded or displaced fraction of pure oil and the latter to the invading fraction or brine in each of the tests. While the dim spot separating the two types of amplitude artifacts should correspond to a certain interfacial region or zone. Repeated observations overall confirm the existence or flow of two pure phases as oil and brine separated by a mixed phase; providing a basis for a detailed evaluation further to examine other anomalous subtleties more resolvable in velocity i. e., ultrasonic wave velocities, and amplitude examination. Velocities are estimated from the first arrivals or breaks of the P- or S-waveforms or modes in each trace, and the integrated amplitudes for each are calculated as the sum of the rectified waveform amplitudes and are analogous to the total area enveloped under the waveform. The integrated sums are not normalized to avoid any apparent loss of information or statistical obscurity. The individual amplitude coefficients or magnitudes are determined from Eulerian or complex components.

In Fig. 11, *a*, the ultrasonic velocities variation curves computed on the basis of effective or wave propagation length for all three experimental tests are presented adjacent and together. Given the information of Fig. 10 in hind sight, Fig. 11 shows conspicuous differences in velocities corresponding to the time of existence of oil and brine. There, however, is a marked and

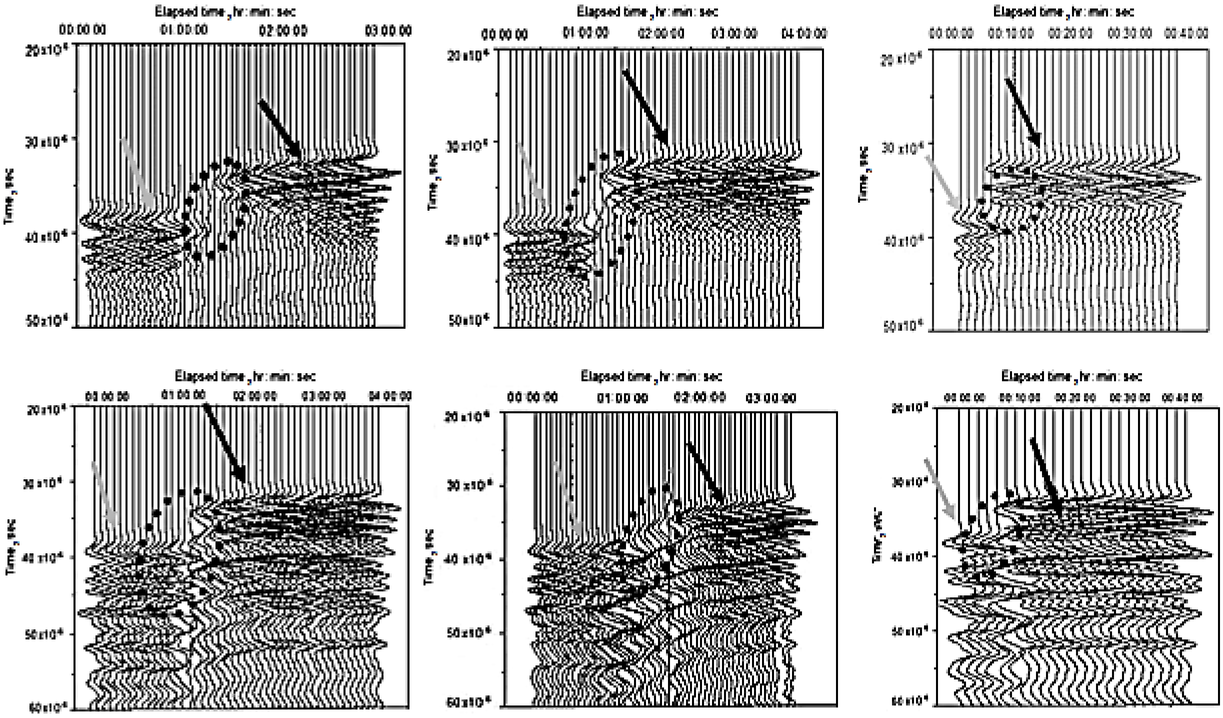


Fig. 10. P-wave (top) and S-wave (bottom) ultrasonograms of three immiscible displacement tests juxtaposed with conspicuous anomalies or features of interest marked (encircled dim spots separating oil and brine flow markers), as other features related to diffraction and interference effects also become contrastingly visible
Left Test 1 (0.044 ml/s), middle Test 3 (0.11 ml/s) and right Test 2 (0.64 ml/s)[5]

Рис. 10. Ультразвуковая сканограмма P-волны (вверху) и S-волны (внизу) для трех опытов с несмешивающимся смещением, совмещенных с выраженными аномалиями или отмеченными изучаемыми особенностями (обведенные в круг «тусклые пятна», которые разделяют маркеры потоков нефти и рассола), так как другие особенности, связанные с дифракционными и интерференционными эффектами, также отчетливо видны
Левый опыт 1 (0,044 мл/с), средний опыт 3 (0,11 мл/с) и правый опыт 2 (0,64 мл/с)[5]

gradual increase in the velocity at the instances indicating a formation of interfacial zone for all three tests, suggesting an acceleration and / or gradient effect, but not a sudden shift or jump, given specifically the length scales under consideration. P-wave velocity variations, in Fig. 11, *a*, thus unambiguously and clearly show P-wave sensitivity to fluid density, in addition to background density. A marked, similar, difference in velocities for oil phase and brine phase, following Fig. 11, *b*, could be readily pointed out in S-wave velocities, respectively. Both wave velocities are at a consistent stable value for the duration of oil saturation, and then begin to increase during the period of mixed phase saturation. Stabilization of the velocities at a higher value indicates the final flow of brine saturation phase. Importantly, in addition, the slope of increase of the velocity in curves, with a significant spread of distribution of well identified individual readings unambiguously confirm initial speculation of a possible degree of miscibility and its flow rate dependence.

Corresponding, integrated amplitude variation as shown in Fig. 12 fixed identically against an elapsed time provides further insights, especially into the nature of the interface, with further confidence, from a subsurface fluids displacement perspective. Occurrence of significantly low amplitudes artifacts or anomalies collectively confirm a very distinct fluid-fluid boundary or fluid front type interface with a characteristic low energy transmission or high dissipation. Such artifacts of amplitudes variation of Fig. 12 appear straightforward to infer however, similar and those of Fig. 12, *b* contain much detailed information to be resolved for disambiguation. In case of Test 2, for example, the artifact of significant amplitude loss after a slight increase, much clearly visible for the cases of Test 1 and Test 3, appears to be unidentifiable; however corresponding

[5] Citation removed as of initial review policy.

a

b

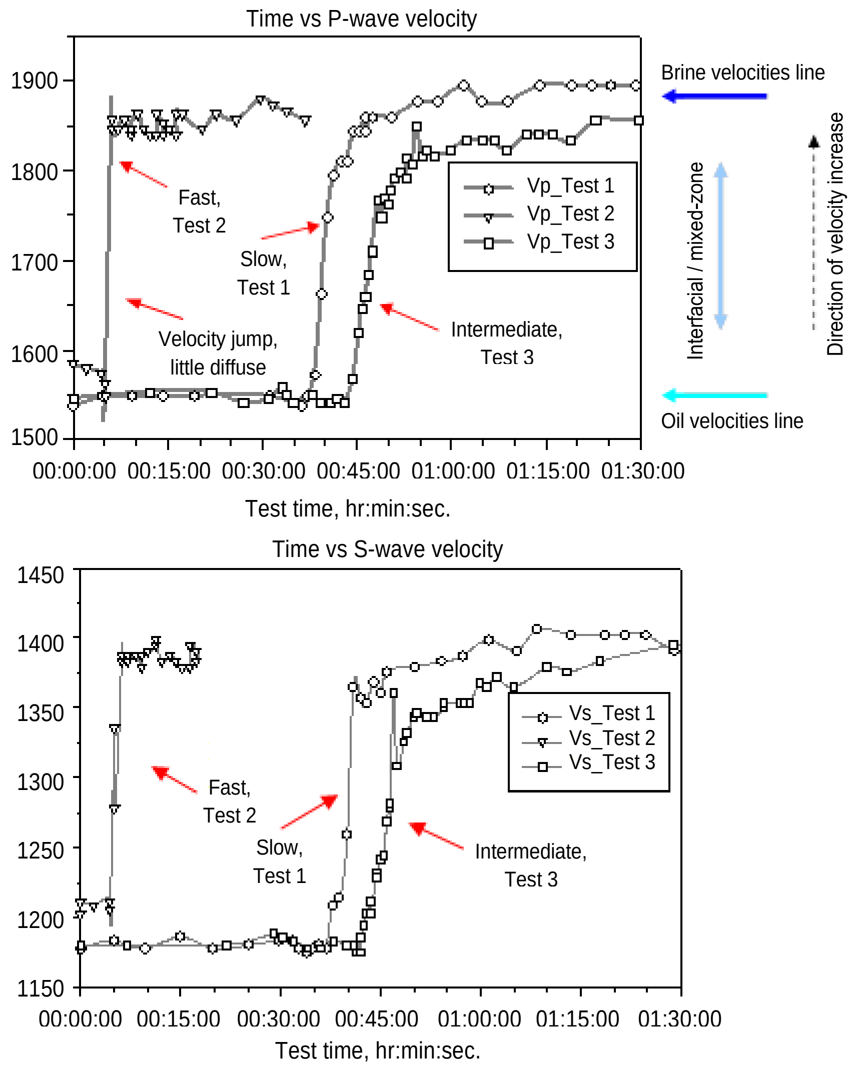


Fig. 11. P- and S-wave velocity variation for all tests:
a – P-wave velocity variation for all tests corresponding to occurrence of different possible phases;
b – S-wave velocity variation for all tests corresponding to same occurrences as depicted in (a)

Рис. 11. Изменение скорости P- и S-волн во всех опытах:
a – изменение скорости P-волны во всех опытах, соответствующих наступлению различных возможных фаз;
b – изменение скорости S-волны во всех опытах, соответствующих тем же явлениям, что и в (a)

information of Fig. 12, *b* fills the gap, understandable from further discussion. The artifact of amplitude loss points to or allows deducing the interface being a typical energy release defect with the meanings of axis of phenomenological thermo-mechanical conversion comparable to minimization of entropy, where mathematical implications for further understanding are available in [41]. The excessive energy loss possibly may include such contributions as more physical aspects and causes of immiscibility in nature, such as slip and, squeeze and collision associated with “fluid bodies” of miniscule dimensions whether integrating with or disintegrating from the interface. This is in addition to other controls or effects of density and viscosity differences of fluids and solid at the interface given also offering purely kinetic implications of surface tension as discussed. Further details for such parametric or factor effects could be understood from [42, 43]. Given, further, the nature of background matrix it could be deduced and understood that interplay of such psychical occurrences in the flow process with their evolution would cause and also be effected by elastic wave diffraction and interference as of concepts described in initial discussion i. e., granular packing mechanistic aspects, contributing to wave damping and amplitude loss. It also could be argued and inferred that viscous effects may have a more pronounced visible or sensible effect or control of wave damping and energy dissipation compared to that of density in the observed and examined parametric data. Differences in the magnitude of the stable level amplitudes corresponding to pure immiscible fractions or saturations as shown in Fig. 12 since is not as large in comparison to the difference in the corresponding velocity magnitudes shown in Fig. 11, for the difference in the magnitudes of the density and viscosity of the oil and brine phases and the characteristic sensitivity of elastic wave propagation. Further the amplitude artifacts of mixed-zone are better resolved against the background compared to that of corresponding velocity variations or related artifacts.

In Fig. 12, *b*, S-wave amplitude variations for Test 2 (extreme left, curve of points shown in inverted triangles) show a very short duration of the existence of the interfacial layer, with the amplitudes corresponding to pure phases / saturations being much lower in magnitude compared to those of Test 1 and Test 3, or to the same information of Fig. 12, *a*. It also, does however depict an amplitude increase followed by a loss of same subtly confirming existence of an interface though not prominent, obscure in Fig. 12, *a*, as indicated. A decrease, similarly, in the duration of occurrence of mixed-zone coincidental with, and corresponding to, amplitude loss is also observable. These artifacts defining the existence of mixed-zone in a narrow space-time window indicate a local flow rate increase in addition to confirming a higher global fluid mobility. Interestingly also, and further, such fluid flow effects, though more subtle

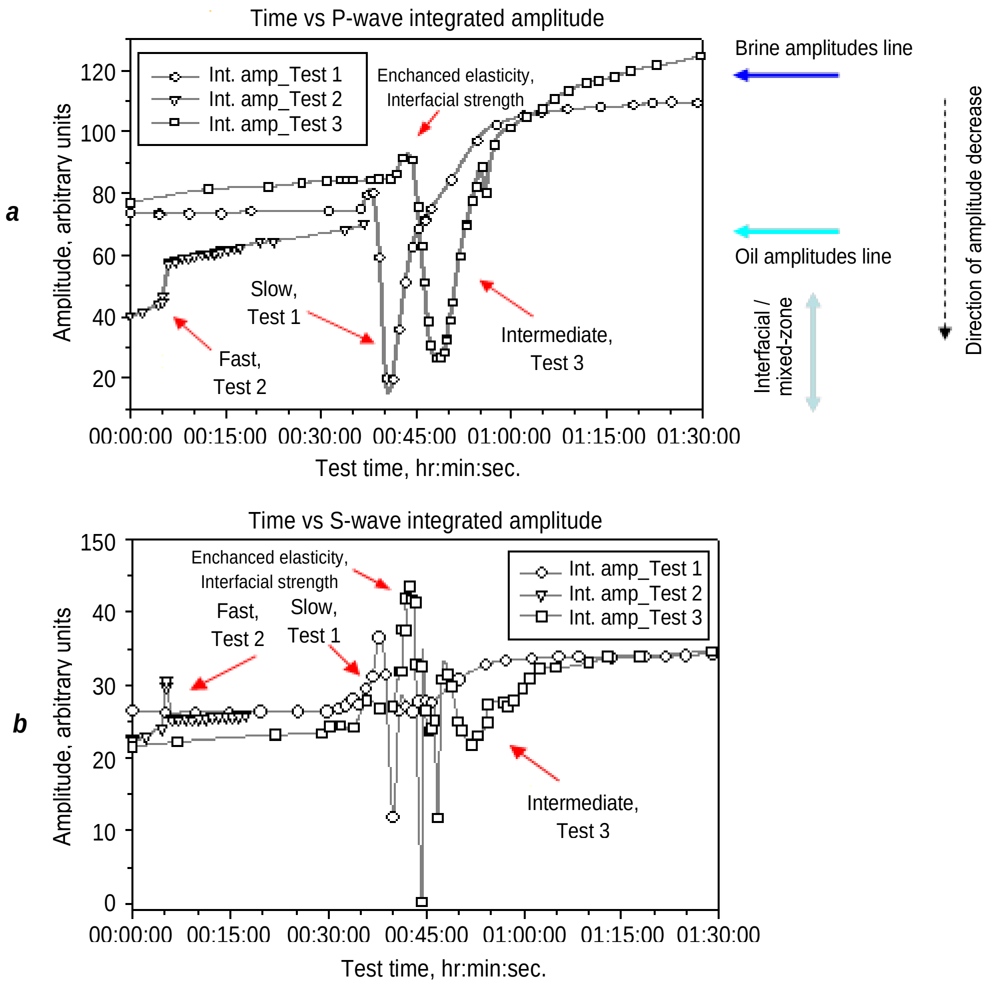


Fig. 12. P- and S-wave integrated amplitudes variation for all tests:
a – P-wave integrated amplitudes variation for all tests corresponding to occurrence of different possible phases and identified features of interest;
b – S-wave integrated amplitudes variation for all tests corresponding to same occurrences as in (a)

Рис. 12. Изменение интегральных амплитуд P- и S-волн для опытов:
а – изменение интегральных амплитуд P- волны для всех опытов, соответствующих возникновению различных возможных фаз, а также соответствующих выявленным изучаемым особенностям; b – изменение интегральных амплитуд S-волны для всех опытов, соответствующих тем же случаям, что и в (a)

could also be identified for the other two (processes) cases of Test 1 and Test 3. If, where in a converse sense, the existence of mixed-zone is well defined and spread in space-time, as amplitude effects it shall correspond to a slow local flow rate and also lower mobility but more “diffuse” mixed-zone or mixed phase.

These observations, in retrospect, can be correlated to information of Fig. 11. In this regard velocity variation, since in Fig. 11, *a*, corresponding to transition from oil phase saturation to brine saturation for Test 2 process is quite steep, as velocity for the mixed-zone almost approaches that of the brine in a short duration comparatively. S-waves velocity variation, depicted in Fig. 11, *b*, further generally corroborates the information and inferences of Fig. 11, *a* for corresponding curves of Test 1, Test 2 and Test 3. Additionally and more importantly S-wave information of Fig. 11, *b* also clarifies and resolves not only any ambiguities regarding existence of the interfacial zone, observable as Test 2 curve significant velocity jumps or variations and not visible in corresponding curve of Fig. 11, *a*, but also allows understanding of two important and useful characteristic aspects. Firstly that the added confidence of time-space localization of the interfacial zone may allow a reliable description of it’s morphology by an efficient collective inferring of data, and secondly that S-waves can prove very useful in providing better resolution in certain geometrical topologies and situations, possibly for differences in frequency content, for comparable P-wave velocity where further discussion is beyond the scope of document.

Given the discussion immediately above and with reminiscence of the constituents of system at hand, it is deducible from collective data examination that the narrower the duration in amplitudes spread, steeper the slope of velocity in gradient. The duration, further or time of observed existence of mixed phase saturation is marked by consistently and significantly damped P-wave amplitudes in magnitude compared to those of pure phases or saturants, and S-waves amplitudes that fluctuate between amplitudes both higher and lower than those of single phase amplitudes. This is clearly observable at the (elapsed) test time instances of 50 min, 1 hour and 5 min after the onset of the flow of the invading fraction / brine in all three tests, respectively. This exactly correlates with the time of the dim spots identified in Fig. 10. In addition to manifesting significant sensitivity in velocity (strength type) measurements, the collective amplitude examination, importantly, also confirms greater sensitivity of the S-wave amplitudes while transmitted through heterogeneous medium i. e., mixed phase saturation, which is due to S-wave inherently characteristic polarized and mode altered propagation.

Another important aspect, that of wave damping or amplitude loss due to contribution both of or as an indicator of (a) local and (b) mobility or say global flow rate effects could be discussed, noticed above. A combined assessment of P- and S-wave velocity and amplitude graphical results, confirm that an increase of flow rate during the fluid displacement type process can cause an early break through by such mechanisms comparable to an onset of plumes or fingers of the brine phase or saturation, such as the identified mixed phase or interfacial zone. Due to deformation and evolution of the interface, plumes formed would advance ahead of the stable interfacial front, a presumed monolayer in the case at hand, possibly due also to viscous fingering effects. This is deducible from examining Test 2, in detail as there is little indication of a smooth of more diffuse transition zone in comparison to consideration of corresponding and similar, artifacts and effects respectively, in Test 1 and Test 3 where an existence of well defined transitioning zone could be inferred.

In summary, and wider perspective, the examination of ultrasonic data or measurements, and that of time domain, velocities and amplitudes magnitude records for the case at hand assumes not only laboratory scale investigations significance it also enhances understanding of field scale applications, implications. Foremost, the laboratory scale simulation of immiscible-displacement set an example for modeling similar porous media flow associated processes, as state-of-the art method. Such simulations are significantly useful in designing, developing and constraining computer simulations, by multiple analyses post experiment other than immediate visualization. The anticipated components or embodiments not only of the process of interest i. e., immiscible displacement for example were vividly observable as well explicable outcomes much to success but also offered further insights; especially the observation of interfacial region occurrence and evolution with implications of fluid-fluid and fluid-solid interactions. Such complex surface tension related effects, as observed, with direct implications on immiscible-displacement efficiency are also reported elsewhere. The surface tension, for example, contorl as of [44, 45] has been emphasized to regulate wettability and effect efficiency of immiscible displacements, and interfacial tension was found or predicted to be sole factor to cause low recovery. In their experimental modeling [46] have arrived at similar conclusions from a geo-environmental remediation perspective (i. e., NAPLs and LNAPLs), observing that efficiency of such "flooding and displacements" processes depends upon factor of "wetting and nonwetting" and comparable issues affecting the interfacial region significantly. In their stochastic models [47] speculate and investigate contribution of the gravity difference (density) based buoyancy effects upon the immiscible interface or boundary / front stability. They propose that immiscible interfacial spreading by deformation or evolution and stability could both be affected by gravity difference and (material and otherwise overall) heterogeneity depending upon length scale.

In field scale sense, and regardless of objective, it thus is well clarified that in immiscible displacement and comparable processes, an early break through may occur when the invading fluid is injected at a much increased flow rate (a higher mobility) and it starts flowing downstream well before displacement of the invaded phase is completed, confirming fluid flow rate control and dependence, and requirement of an optimal flow rate, in implementation of such a process. It, further is also deducible that in case for example of contaminants or pollutants subsurface transport or flows, with possibly varying degrees of ground water or otherwise dissolution in sediments, physical composition and morphology of the flows could be complex in occurrence and fate; meaning that multiple flows constituents could independently and separately co-occur, as if in an inert equilibrated state with well defined interfaces or fluid fronts and boundaries without any (physical or chemical) evolving interaction within or with surrounding environment, while at other instances there could be certain distinguishable degree of interactions and miscibility with diffusion into surrounding environment.

In geophysical inferring of near surface and / or near field, thus, one may confront or contend with the situation of dealing with the detected geophysical data or information beyond the expected regarding any anticipated targets due both, either to the "incomplete" understanding of the method or that of the possibilities of the process of interest, and so integration of data and / or methods could provide the much needed resolution.

Adequacy of observations and analytical verification

Assumption of adequate resolution in terms of the probed length scales in size range from a single bead or grain, few beads, compared further with the propagation length, holds for plausible interpretation. Maximum wave propagation length of about 5cm with transducer diameter "d" being 13 mm and a grain or bead size of 0.5 mm, suffice for meeting the criterion of adequate resolution attainment [48], i. e., $d = 4\ \lambda$, with input amplitude dynamic control, considering the packed core system as sediment aggregate, to remind. Reliability of methodology and adequacy of the resultant outcomes is established by comparative assessment with works of [49, 50] and others relevant, cited by them. Analytical verification is implemented by using functional description or models of Gassman and Biot theory comparable to a numerical approach i. e., high and low frequency closure. The expressions in compact form are briefly described by following equations, and are eventually used for P-wave velocities estimates. Various input quantities for a fluid substitution type analysis for each saturation type, are described in Table 1 with appropriate units, in appendix. The relation of phenomenological density terms ρ_{ij} of Biot theory to those of granular pack properties as described in the equations, are well known, and derived and described in [51]. Usual analytical equations (1–6), to determine P-wave velocities using Gassman fluid substitution method are given below;

$$V_{P_{sat}} = \sqrt{\frac{K_{sat}+(4/3)G_{sat}}{P_{sat}}}, \quad (1)$$

$$K_{sat} = K_{solid}\left[\phi K_{dry} - \frac{(1+\phi)\frac{K_{fluid}K_{dry}+(4/3)G_{sat}}{K_{solid}+K_{fluid}}}{(1-\phi)K_{fluid}+\phi K_{solid}-\frac{K_{fluid}K_{dry}}{K_{solid}}}\right], \quad (2)$$

$$\rho = (1-\phi)\rho_{solid} + \phi_{fluid}, \quad (3)$$

$$G_{sat} = G_{dry}, \quad (4)$$

$$K_{dry} = \rho\{(V_p^2) - 4/3(V_s^2)\}, \quad (5)$$

$$G_{dry} = \rho(V_s^2). \quad (6)$$

The graphical illustration of Fig. 13 depicts or tends to advocate the adequacy of the inferred outcomes of the three experiments of the dynamic immiscible displacement study. It is clearly observable that the two solutions naturally provide an upper and lower bound for the experimental measurements. All three experiments are represented by quasi static state descriptors given as Oil phase, Mixed phase and Brine phase. Oil phase point is a single minimum possible velocity chosen to identify existence of 100 % oil saturation. Brine phase point or points, in a similar sense correspond to a maximum velocity point perceived to represent 100 % brine saturation. These two points are not averages of various observations but two extreme readings to provide a sense of minima and maxima, statistically meaning that the values provide for strict bounds and any trends, considering corresponding observations of all experiments will only fall and clustered within described bounds. The Mixed phase points are calculated by applying a usual fractional weighted averaging method to a spread of values, contrary to choosing a maxima and minima from the spread, to account for variability of fluid fractions in mixed phase saturation for an adequate both parametric sense and sensible positioning of the representative estimated value within the bounds. Thus for a certain spread of values of the dynamic process precise representative static values are generated.

The drained bulk and rigidity moduli (dry frame moduli) are estimated from the ultrasonically determined velocity measurements. In order to understand the response of the form of conventionally adjusted models of fluid substitution type analyses chosen i. e. Gassman and Biot, the adjusted and unadjusted values of these dynamic moduli were used for input. Adjustment of the frame bulk modulus is suggested at various instances regarding such analyses as emphasized by [52, 53] to account for or create real porous rock effects. Both the adjusted or unadjusted moduli along with the information of the other petrophysical (porosity, density etc.) properties are used in the analysis, after creating composite bulk moduli and densities of the saturated porous media. Gassman equations and Biot equations in simplified functional form, as presented, with estimates of adequate corresponding inputs are used to estimate P-wave velocity values of the saturated medium. Analyses are performed for all three saturants using the drained strength information or moduli. After several analyses and trails with adjusted and unadjusted frame bulk

Table 1. Properties of constituents of laboratory unconsolidated core analogue
Таблица 1. Свойства компонентов лабораторного неуплотненного аналога керна

Property	Value
Bead / grain dia.	0.5 mm
Bead / grain material density (ρ_s or ρ_{solid})	2.5–2.6 Sp.gr. approx.
Grain material bulk modulus	4.39 GPa
Porosity of granular pack (Ø)	26 v/v %
Structure factor of porous granular pack (α)	2.4 dim. less
Adjusted / measured frame bulk modulus (K_b)	4 GPa
Measured frame shear modulus (N or G)	2.44 GPa
Mineral oil / displaced fluid density (ρ_f oil)	0.761 Sp.gr
Mineral oil bulk modulus (K_f oil)	1 GPa
Mineral oil viscosity	10 cP
Brine / displacing fluid density (ρ_f brine)	1.028 Sp. gr
Brine salinity	3.5 w/v %
Brine viscosity	1.3 cP
Brine bulk modulus (K_f brine)	2.45 GPa
Fluid mixed-zone bulk density estimate (ρ_f mixt.)	0.891 Sp.gr

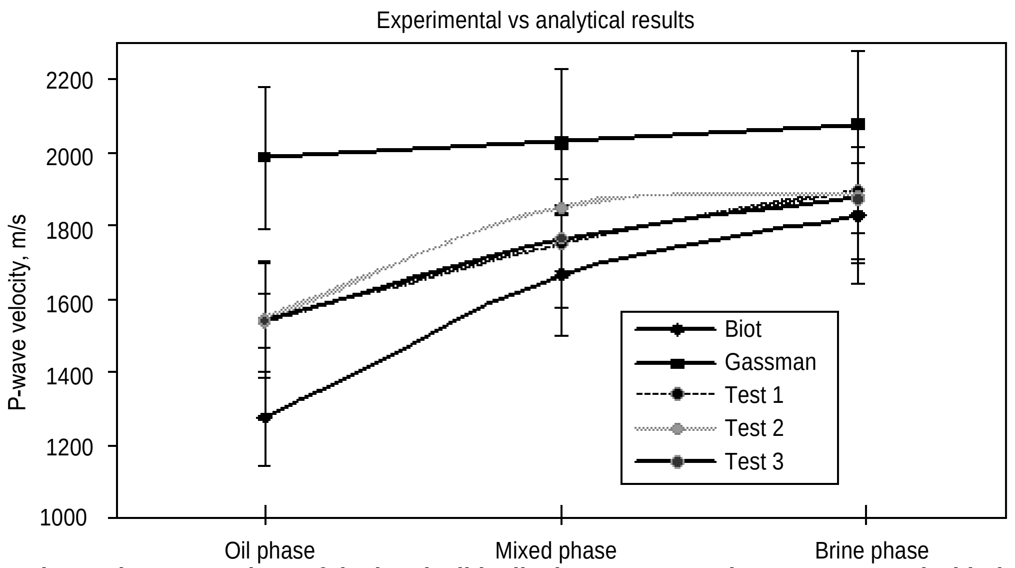


Fig. 13. Experimental P-wave values of the immiscible displacement experiments compared with the analytical results generated by usual models of wave propagation based on Gassman and Biot theories

Рис. 13. Экспериментальные значения P-волн в экспериментах по несмешивающемуся смещению по сравнению с аналитическими результатами обычных моделей распространения волн, основанных на теориях Гассмана и Био

moduli and any other associated parameters, certain important facts especially given anomalous behavior of granular porous media were understood. Provided further with an understanding that the analyses were not to test the limitations of the theory to examine a "data fit", the analyses were rather done to examine the adequacy of the experimental outcomes in a predictive sense. In holding with an empirical nature or sense of inputs, the restriction of constancy of rigidity with complete disregard of saturation effects i. e., conventional $\mu_{sat} = \mu_{dry}$ of frame, was maintained, with the fact in hind sight that a zero frequency solution is sought from ultrasonic measurements. Further for guessing or estimating solid grain and frame bulk moduli in a suitable range, another restriction to be taken in consideration was that the ratio of K_{dry} / μ_{dry} (for dry or drained frame) should not be less than unity, if possible which is brought to attention with illustration and citation of several references regarding fluid substitution exercise by [54]. Resulting outcomes, after addressing the restrictions and the associated computational issues of the experimental and analytical nature corresponding to the analysis, are plotted a fixed points with error bars. The outcomes reasonably populate or fall within one standard deviation, as in Fig. 13.

The S-wave results are not plotted for inability of the models to provide stable solution marked by significant underestimation. This might be affected by, a speculated, significantly strong bearing of viscosity on strength moduli for the un-cemented and un-sintered unconsolidated material evaluated. In such analyses, [55] has pointed out that fluid effects upon seismic (or acoustic) signatures in unconsolidated sediments are not only controlled by fluid bulk moduli but are influenced by viscosity effects too. In an indirect sense it is deducible that the effects of viscosity upon rigidity of a stiff porous frame are different from that of a granular frame. The significance of the reliability of verification draws upon two factors. Firstly that the dry matrix / frame shear and bulk moduli were ultrasonically measured by same procedure used in the displacement experiments, and adjusted for any residual saturation effects before other estimations. Secondly not only that analytical velocity values determined predicted the velocity values corresponding to pure saturations but also and interestingly the velocity estimates for mixed phase were statistically plausible.

Concluding remarks

Effectiveness of integrated methods by examining P- and S-wave chronographic including velocity data for reliable characterization of near surface contaminant flow processes, in unconsolidated sediments is demonstrated. Rationale of emphasis, further, is drawn upon the need for understating physical and chemical dimensions or aspects of both the anthropogenic and natural stressors of near surface; with implications and challenges of subsurface geophysical inferring due to creation of complex surrounding or local geological system confining such flow processes. Some well fitting examples, in this regard, of possibilities and situations of stressors covering local to regional geological settings and factors from past and also present are cited and explained. A simplified connection towards describing and examining such effects is draw by evaluating an analogue situation of immiscible displacement process occurrence through a granular material packing stimulated by P- and S-waves, including effect also of re-packing and re-saturation.

P-wave ultrasonic velocities magnitudes, including the time-sections or records with other data patterns within, were unambiguously supported by corresponding S-wave data. Both P- and S-wave data correlated well and allowed unambiguously identify three separate regions or components of the monitored or imaged flow process of interest. These were high-density brine saturated zone, a low-density oil saturated zone and more importantly a medium-density mixed-zone in parametric sense; manifested as extremes of higher and lower velocities, separated by a spread of intermediate velocities respectively. Apart from velocities, P- and S-wave integrated amplitudes, both were observed much damped or lowest for interfacial zone but remained higher for brine saturated zone compared to those of oil saturated zone. There was satisfactory correlation in amplitudes data too. The fluctuation of S-wave amplitudes for the mixed or interfacial zone was however much pronounced, compared to that of P-wave, depicting a greater S-wave sensitivity, unexpectedly. It clearly defined an energy dissipation marker, of an oil-water type interface, with a polarization affectation or dependence of transmitted ultrasonic energy. Further a noticeable characteristic spike in S-wave amplitudes fluctuation, for the same zone, not prominent in P-wave ones, indicates rigidity properties, meaning that the identified interfacial region is well bounded as a monolayer type feature manifesting or assuming a structural consistency with strength. In addition, both velocity and amplitude sensitivity of interfacial stability in evolution and degree of mixing, as a pluming or viscous fingering effect, with a direct dependence on flow rate, could also be deduced and / or assessed form examining the velocity variation slopes. These two aspects, vital finding, would have been difficult to infer from P-wave data only.

It is also interesting to infer that S-waves, for adequate bandwidth, can appropriately see where P-wave may be blinded such as variation of rigidity effects. S-waves interestingly also reveal a proportionately higher sensitivity to confined fluids at the scale of interest or observation discussed. Plausible analytical confirmation of the experimental results by usual models not only show their usefulness in assessing a dynamic process in terms of static points but also reveal that S-wave characteristics in the models are not appropriately accounted for. The results not only show possibility of attaining a greater resolution by integrated acoustic field surveys for flexibility of being able to exploit combination of different polarizations, bandwidths and energy levels suited to situation and purpose, but the use of such techniques for nano-scale process synthesis, control and characterization could be appreciated.

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Information about the author / Информация об авторе

Bilal Hassan,
PhD,
Researcher Earth Science and Engineering,
Memorial University of Newfoundland,
St. John’s, Canada,
p94bh@mun.ca,
https://orcid.org/0000-0002-9373-8922,
http://scholar.google.ca/citations?hl=en&user=ubkN1-cAAAAJ.
Хассан Билал,
доктор наук,
исследователь в области наук о Земле и технических наук,
Мемориальный университет Ньюфаундленда,
г. Сент-Джонс, Канада,
p94bh@mun.ca,
https://orcid.org/0000-0002-9373-8922,
http://scholar.google.ca/citations?hl=en&user=ubkN1-cAAAAJ.

Contribution of the author / Вклад автора

The author performed the research, made a generalization on the basis of the results obtained and prepared the copyright for publication.

Автор выполнил исследовательскую работу, на основании полученных результатов провел обобщение, подготовил рукопись к печати.

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