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# Krauklis Wave - Half a Century After

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## SUMMARY

Half a century after the original publication by Pavel Krauklis in 1962, the slow fluid wave in a fracture filled by fluid has got the name of its discoverer. This is the seventh personal name given to an elastic wave and which is now standing in a row with other remarkable scientists: Rayleigh, Love, Lamb, Stoneley, Scholte, Biot. The Krauklis wave is a slow dispersive wave mode that propagates in a fluid layer bounded by elastic media. There are indications that Krauklis wave plays a significant role in a variety of wave propagation phenomena in seismology, acoustics, engineering and hearing physiology. It is distinct by its large amplitudes, high dispersion and confinement to the fractures filled with fluid. In the prospecting seismology Krauklis wave might be an important component of the hydro-fracturing process, seismic wave propagation in fractured reservoirs, and fracture detection.

## Introduction

Until recently, six waves in Dynamic Theory of Elasticity were named after their discoverers. It is remarkable that all those waves were found and predicted theoretically as the results of mathematical and physical approaches in Nature exploration to be later confirmed in experiments and used in various scientific and practical applications. In 1885, Lord Rayleigh[1] had published a paper where he described a wave capable to propagate along a free surface of an elastic half-space. Later (1904) Rayleigh had become a fourth Nobel Prize winner in physics for his work on densities in gases. His results in elastic wave propagation had also left an outstanding impact on further development in this field. In 1911, Love[2] had considered a pure shear motion for a model of an elastic layer, bounded by an elastic halfspace. Nowadays, Love wave is a powerful instrument of subsurface studies in engineering and seismology. In 1917, Lamb[3] had discovered symmetric and asymmetric waves propagating in an isolated elastic plate, which are now widely used in non-destructive material testing. Stoneley[4] (1924) had found that a surface wave can propagate along an interface between two elastic halfspaces for some parameter combinations, and then Scholte[5] had shown in 1942, that in a model where one of the halfspaces is fluid, the surface wave can exist for any parameters. Scholte wave is one of the main research tools, especially in marine seismology. The sixth wave was named after Biot[6] (1956), and it describes a slow diffusive wave in a fluid-saturated poroelastic media. Importance of such a model is hard to overestimate as most of fluids including different fuels are stored in the underground porous rocks. That is the list of six great men whom left the long living legacy in the science of wave propagation. The time has come to add one more name to this list.

## Krauklis wave

It is both an honour and privilege for us to state that from now on the seventh personal name is given to a remarkable and important wave, which was discovered half a century ago. It is given to a "slow fluid wave" after its first finder Pavel Krauklis (1933 -2010), an applied mathematician, who devoted all his professional life to the theoretical studies of wave propagation in layered elastic media. He started his career as one of the many talented students of G.I. Petrashen - the founding Father of Russian School of dynamic elasticity. Krauklis worked in St. Petersburg branch of Steklov Mathematical Institute (Russian Academy of Sciences). He had published more than 180 papers, including three monographs.

**Pavel V. Krauklis**
Around 1962 (left) and in 2003 (right).

In 1962 Krauklis[7] had found a dispersive fluid wave in a system of a fluid layer bounded by two elastic halfspaces with different material properties. This wave shows a strong dispersion with phase velocity approaching zero as frequency approaches zero, and it is polarized primarily along the interfaces. Physically, the wave is supported by the elasticity of channel walls, which resist inertia of the fluid. In a thin layer, a small vertical displacement of the walls causes large horizontal (along the layer surfaces) displacements due to conservation of mass in the low-compressible fluids. Amplitudes of the wave are frequency-independent at low frequencies. At some layer depth there is a point, where vertical component is zero. The main polarization of the wave lies along the layer walls. At high frequency limit the slow fluid wave becomes a nondispersive Scholte wave.

For a long time, a propagation of the Krauklis wave was evasive for the conventional numerical modelling approaches, such as finite-difference and finite element methods. That was seemingly counter-intuitive that the models can support waves with velocities by several orders of magnitude smaller than those defined by material parameters. Spatial discretization based on a smallest model velocity (a standard "rule" in numerical simulations) inevitably misses such a delicate wave phenomenon. At the same time use of the highly variable grids enables to model the Krauklis wave as it was recently done by Frehner&Schmalholz[8] (2010) using a finite-element (FE) method, and by Shigapov&Kashtan[9] (2011) using a finite-difference (FD) method. Examples of their results are shown on Figures 1 and 2, and demonstrate high amplitudes of the Krauklis wave and its confinement to the fracture interior.

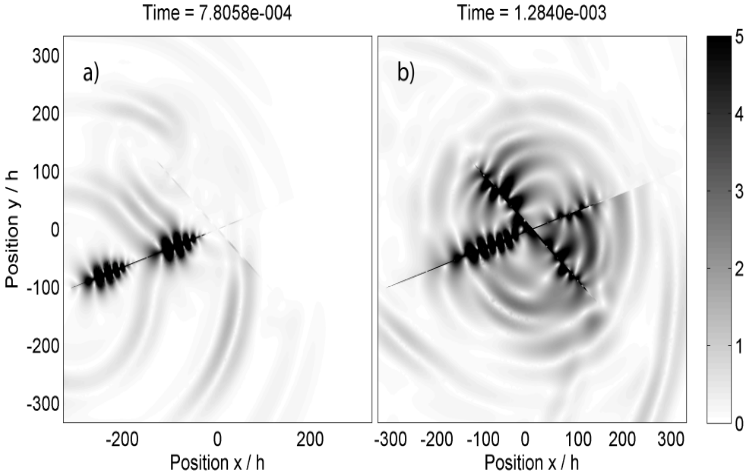

**Figure 1.** FE modeling for the intersecting fractures model (Frehner&Schmalholz[8], 2010).

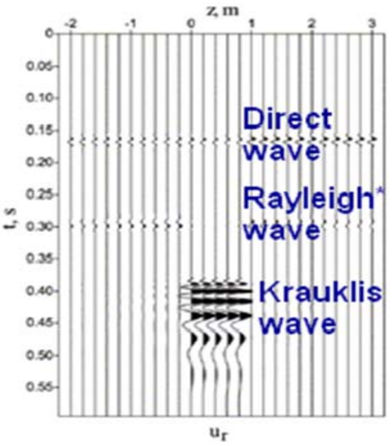

**Figure 2.** FD modeling (Shigapov&Kashtan[9], 2011)

## History of Krauklis wave research

After the original work (Krauklis[7], 1962), the slow fluid wave was independently found as a numerical result by Lloyd and Redwood[10] (1965) for a trilayer model, and by Paillet and White[11] (1982) for the identical halfspaces, as a root of a correspondent determinant for a linear system representing boundary conditions. Chouet[12] (1986) suggested that "crack" wave, caused by a molten rock in a lava conduit generates low-frequency tremors before volcanic eruptions, which was later supported by Ferrazzini and Aki[13] (1987). Tang and Cheng[14] (1988) had observed slow wave in the laboratory at MHz frequency range. Ferrazzini et al.[15] (1990) reported detection of those waves in field data during hydrofracturing. Goloshubin et al.[16] (1994) found the slow wave in a hydrocarbon reservoir using cross-well seismic. Groenenboom and Falk[17] (2000) had compared fluid-filled and dry cracks using finite differences, and found a large amplitude wave at late arrivals in the fluid-filled case. Korneev[18] (2008) has extended the analytical results to the case of viscous fluids. His computations predicted an existence of the fluid wave resonances for the oil bearing fractures at seismic frequencies. Frehner and Schmalholz[8] (2010) numerically studied a reflection of the fluid wave from the fracture tip and found rather high reflection coefficient values, which is another argument in the favor of resonant scattering of the fluid waves in the fractures. In an "unusual" development Bell and Fletcher[19] (2004) had suggested that slow fluid waves play a key role in the human hearing physiology. They argue that a cochlear in an inner ear (which has 10 micron thickness and about a hundred micron in length) acts as a resonator and amplifies acoustic wave energy before transferring it to the nerve receptors.

The separate part of history in studying the Krauklis waves belongs to Krauklis himself. After some time since his original publication he devoted more of his attention to this topic. In particular, he investigated attenuation of the slow wave and demonstrated that the attenuation can be very small, if the layer thickness is much less then the wavelength (Krauklis et al.[20], 1992). He also investigated an interference slow wave propagating in a cracked fluid-filled layer (Krauklis and Krauklis[21], 1998) and in poroelastic Biot layer (Krauklis and Krauklis [22], 1999) sandwiched between two elastic half-spaces. It was proposed, that the attenuation of the slow wave in such layers is induced by fluid inelasticity and shown that attenuation of the wave at low frequencies can be very small, and there is a possibility of slow wave observation in the real field seismic experiments, in particular during cross-hole measurements. Later he investigated the slow wave in the layer consisting of the alternating liquid layers: water-oil, water-gas, oil-gas (Krauklis and Krauklis [23], 2001) where the material in the layer behaves as an effective anisotropic fluid. In his latest work (Krauklis and Krauklis [24], 2002), he considered a case of a two-layered fluid modeling different fluid separation in a hydrocarbon reservoir.

In the cited literature, the slow fluid wave was known under different names: slow fluid wave (Krauklis[7], 1962; Ferrazzini and Aki[13], 1987), crack wave (Chouet[12], 1986), Stoneley wave (Tang and Cheng[14], 1988), Stoneley guided wave (Korneev[18], 2008; Frehner and Schmalholz[8], 2010), SLR or squirting wave (Bell and Fletcher[19], 2004). There was a growing consensus among the researchers, to name the slow fluid wave after Krauklis, as its first finder. In particular, such a suggestion is made in Maximov et al.[25] (2011). In August 2011, a paper by Korneev[26] entitled "Krauklis wave in a stack of alternating fluid-elastic layers" was accepted for publication in Geophysics. Such title has received the full support by the editors and reviewers of the paper, giving a special respect and a well deserved recognition of Krauklis achievements.

## Krauklis wave and its potential applications

Nowadays, the very important objects of geophysical studies are the fluid-filled rock fractures in elastic materials. Fractures and fracture systems are the main fluid conductors and the Krauklis wave can be a powerful tool for detection, imaging and controlling fractures. Recent developments in shale gas production assume extensive use of hydro-fracturing, which also require fracture evaluation and monitoring. Seismic low-frequency effects above hydrocarbon reservoirs yet have no established physical explanation and the Krauklis waves in fracture networks are likely to be a core part of its mechanism. Large amplitudes of the Krauklis wave are might cause a nonlinearity in seismic wave propagation and can possibly be used for fluid flow stimulation. A full extent of the Krauklis wave use has a great potential and yet to be explored.

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