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Powerful Low-Frequency Vibrators and Outlooks of their Application at Monitoring of Engineering Constructions and at Solving Other Problems of Active Seismology

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Abstract

In the past two decades, active seismology studies in Russia have made use of powerful (40- and 100-ton) low-frequency vibrators. These sources create a force amplitude of up to 100 tons and function in the 1.5-3, 3-6 and 5-10 Hz frequency bands. The mobile versions of the vibrator have a force amplitude of 40 tons and a 6-12 Hz frequency band. Registration distances for the 100 ton vibrator are as large as 350 km, enabling the refracted waves to penetrate down to 50 km depths. Vibrator operation sessions are highly repeatable, having distinct "summer" or "winter" spectral patterns. A long profile of seismic records allows estimating of fault zone depths using changes in recorded spectra. Other applications include deep seismic profiling, seismic hazard mapping, structural testing, stress induced anisotropy studies, seismic station calibration, and large-structure integrity testing. In more detail, these questions are discussed in reports of our colleagues from Novosibirsk. This report is devoted mainly to powerful low-frequency vibrators, their theoretical description and design. Besides, problems of vibroseismic monitoring of engineering constructions are briefly elucidated.

Key words: active monitoring, seismology, vibrators

Introduction

In the 1980's, several institutes of the Siberian Branch of the Russian Academy of Sciences developed a long-term seismic research program based on the use of vibrational seismic sources. An eccentric low-frequency 100-ton-force vibrator was designed, built and tested. The operational frequencies of this vibrator can be tuned to several frequency bands: 1.5-3 Hz, 3-6 Hz, 5-10 Hz. The duration of a vibrator operation may be of any length starting from 5 minutes; while in practice, the average duration is about an hour.

Field works on active seismology have started in 1980, when the seismograms shown below were recorded [1]. The distance of propagation of a powerful- vibrational-source signal is illustrated in Figure 1, where seismograms recorded at 20, 96, 170 and 286 km are presented. In this experiment, the vibrator was working in the 5-10 Hz frequency band. The point of excitation was on the Bystrovka vibroseismic test field, situated on the bank of Obski reservoir, about 70 km south-west of Novosibirsk. (see the map on Figure 2). The registration line was oriented in west-east direction and it was going from Bystrovka to Lake Chany, which is located at a 286 km offset. The duration of the vibrational session was 45 min. For

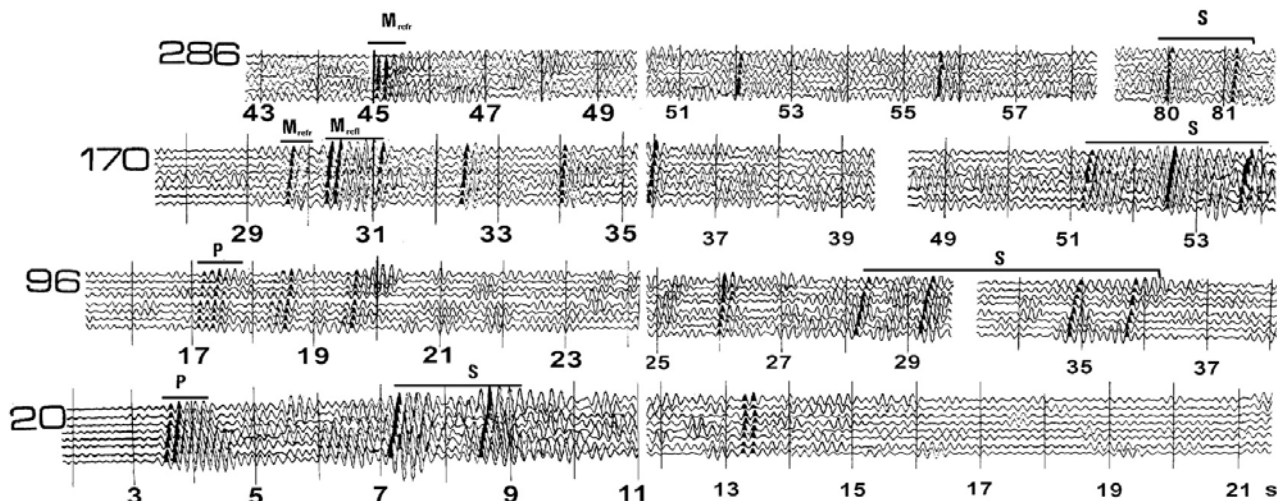


Figure 1. Seismograms recorded at 20, 96, 170, 286-km offset distances from a 100 ton vibrator. For the 286-km offset, the duration of the vibrational session was 45-minutes. Mrefr and Mrefl are respectively the refracted and reflected waves from the Moho discontinuity. In the region of the experiment the Moho discontinuity is approximately 40-km deep.

comparison and discrimination purposes, a surface explosion with 5 ton of TNT equivalent was also made. The explosion site was in the Iskitim quarry close to the Bystrovsky test site. The seismic signals from this explosion were recorded by the same stations at a 286 km offset. The obtained record had the same structure as in Figure 1, although the signal to noise ratio on the explosion seismogram was

lower. In the subsequent years, many similar comparative seismograms were obtained on a routine basis.

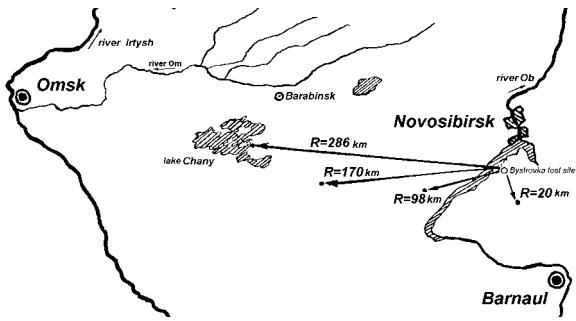


Figure 2. Locations the vibrator and recording profiles for data shown in Figure 1.

The refracted waves, which are cross-correlated with the sweep signal for transforming them to impulse form, have a registration distance $L = 300-350$ km, which is sufficiently large for the illumination of the crust at all depths down to $h=40 - 60$ km. The maximum depth penetration of the refracted waves can be approximately estimated using the expression $h = L / (4 - 7)$.

In a monochromatic (single frequency) mode, the maximal distance for reliable registration of the amplitude and phase of oscillation is at least 1400 km. The registration of monochromatic signals was done on the shore of the lake Balchash.

The use of vibrational sources includes several important applications, which are the subjects of other papers by authors from Novosibirsk (see also [2]). Therefore, in this paper we touch the subject of the vibrator design, and also discuss their applications for integrity diagnostics of the large engineering constructions, such as dams, bridges, large industrial facilities and nuclear power plants.

A photograph of a 100-ton vibrator is given in Figure 3. Visible are columns (standing on the vibro-platform) that support a metal panel. On this panel sits a mass of about $100 \cdot 10^3$ kg. Hence, the net weight that acts on the ground is of about $M_{pl} \approx 120 \cdot 10^3$ kg. It follows that the amplitude of the pressure acting on the ground is no



Figure 3. A view of the 100-ton vibrator.

larger than 0.7 kG/cm^2 . This pressure is similar to the pressure exerted by a shoe of a standing man. As a result the vibro-platform does not compact or otherwise deform the medium, on which it acts; this explains the repeatability of experiments.

Currently, one stationary 100-ton vibrator is installed at the Bystrovsky test site (not far from Akademgorodok), the second one

is close to Babushkino town, near Lake Baikal, and the third vibrator is set in the Krasnodarsky Region.

The described 100-ton source is a stationary structure. For a number of problems, it is necessary to have a mobile vibrator. Hence, a 40-ton mobile vibrator (Figure-4), an analogue of the 100-ton vibrator, has been designed.. (Use of this vibrator is described in the paper by V. M. Soloviov)



Figure 4. A view of the 40-ton vibrator. 1, 2, 3 -platform elements; 4-loading mass; 5-transmission; 6-electric motors.

Nonexplosive Surface Source

A typical design of a nonexplosive (impulse/vibrational) source is shown in Figure 5 [3]. The power chamber, which generates the force F_o^o acts on a platform with mass M_{pl} against an inertial mass M_i . The platform may (or may not) be held down by a load mass M_{pr} .

The load mass M_{pr} may be made disjoined from the vibrations of the platform via a spring of stiffness K_{pr} . The load masses are typically placed symmetrically about the point of action of the force F_o^o . Hence, on Figure 5 we show the load system, which is asymmetrical with respect to the center of the platform.

We model the ground as a spring of stiffness K_{gr} , damper R_{gr} , and attached mass M_{gr} . To simplify the calculations we assume that the platform is never detached from the ground, and $U_{gr} = U_{pl}$. It is enlightening to consider the well-known analogy between mechanical and electrical system, and, hence, we apply Gamburtsev's method.

First, we consider the simplified case, where the parameters of the mechanical structure (M_{pr} , K_{pr} , M_{gr} , K_{gr} , R_{gr} etc.) are constant in time. In the electrical system, the masses are replaced by inductances, the dampers - by resistances, springs - by capacitances, forces - by voltages and velocity - by current. In this design, we may trace a circuit across the inductances M_i , M_{pr} , M_{pl} , and write the equation for voltage in this circuit as $F_i + F_{pr} + F_{pl} + F_{gr} = 0$. Therefore, the force F_{gr} , acting on the ground, is

$$F_{gr} = -(F_i + F_{pr} + F_{pl}), \quad (1)$$

Using the generalized impedances

$$Z_{gr} = p M_{gr} + (1/p) K_{gr} + R_{gr},$$

$$Z_{pr}, \text{ and } Z_{pl} = p M_{pl}, \quad (p \equiv j\omega)$$

it can be seen, that "the current J_{pl} " according to Ohm's law is

$$J_{pl} = F_o / Z_s, \quad Z_s = Z_{pr} + Z_{pl} + Z_{gr}, \quad (2).$$

The force F_{gr} , acting on the ground should have a negative sign, so that

$$F_{gr} = -Z_{gr} J_{pl} = -F_o (Z_{gr} / Z_s), \quad (3).$$

$$J_{pr} = J_{pl} (1 + ja_{pr} x_{pr}) (1 - x_{pr}^2 + ja_{pr} x_{pr})^{-1},$$

$$x_{pr} = f / f_{pr}, \quad a_{pr} = R_{pr} (K_{pr} M_{pr})^{-1/2}, \quad (4).$$

which is the solution of the above-posed problem.

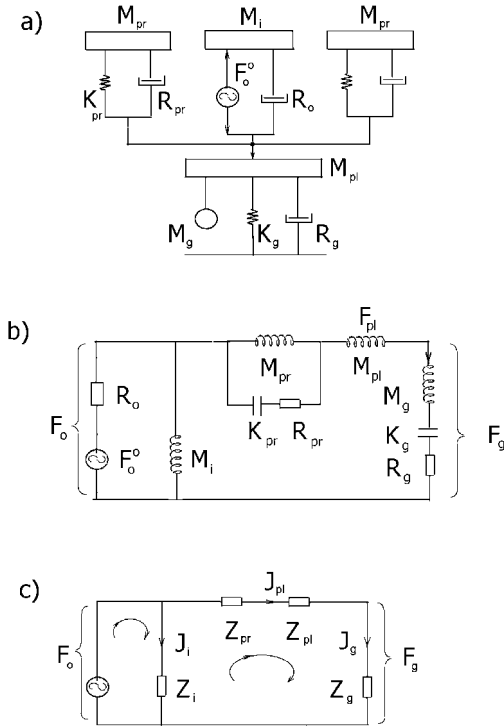


Figure 5. a)-mechanical scheme; b)-electro-mechanical analog scheme; c)-electrical analog with generalized impedances. F_o -force generated by the power chamber acting between inertial mass M_i and the platform M_{pl} . The platform is loaded with the loading mass M_{pr} , which is damped from vibrations using the spring K_{pr} , F_{gr} -force acting on the ground. The ground is represented by the adjoin mass M_{gr} , the spring by K_{gr} and the damper by R_{gr} .

The importance of knowing the force $F_{gr}(t)$ is due to the fact that in a homogeneous half-space, at depth z , and far from the source the displacement of a longitudinal wave is given ([3], p.~72) by: $U_z^p = F_{gr}(f) (2\pi\rho_{gr} V_p^2 z)^{-1}$, where ρ_{gr} , V_p are the density of the medium and the velocity of the longitudinal wave respectively, and $F_{gr}(f)$ is the amplitude of the force $F_{gr}(t)$ for a frequency f . This equation holds while $D \leq \lambda/4$, where D is the dimension of the source (its maximal length or width) and $\lambda = V_p / f$ is the longitudinal wavelength. The formula is

remarkable in that, while $D \leq \lambda/4$ (and this most often holds), the displacement U_z^p does not depend on the area or shape of the surface.

Let us now discuss the principles of choosing the appropriate values for impedances Z_{gr} , Z_{pr} and $Z_{pl} = pM_{pl}$. Ground impedance Z_{gr} can be determined in the following way. Ground is considered as a "black box". We need to evaluate the impedance of $Z_{gr} = F_{gr} / J_{gr} = F_{gr} (pU_{gr})^{-1}$ this "box". Vertical force density (stress) on the surface of the half-space $z=0$ is assumed to be specified on the vibroplatform area S_{pl} . A mean value of the displacement U_{gr} averaged over S_{pl} can be determined by solving an elasto-dynamic problem using methods of Professor Petrashen's school. The obtained results can be presented in the form of power series

$$pZ_{gr} = C_0 + pC_1 + p^2C_2 + \dots, \quad (5).$$

where coefficient C_0 is called a "ground impedance" ($C_0 = K_{gr}$), coefficient C_1 - is an active resistivity of the ground ($C_1 = R_{gr}$), and C_2 is an adjoin ground mass ($C_2 = M_{gr}$).

In a particular case, when on a surface of an ideal homogeneous elastic half space the force F_{gr} is uniformly distributed inside of a circle with radius r_0 , we have

$$K_{gr} \approx 6(1 - \gamma^2) \rho_{gr} V_s^2 r_0, \quad (6);$$

$$R_{gr} \approx 3.8(1 - \gamma^2) \rho_{rg} V_s r_0^2, \quad (7);$$

$$M_{gr} \approx (1 - \gamma^2) \rho_{rg} r_0^3, \quad (8);$$

where ρ_{rg} - is a density of the ground, $\gamma = V_s / V_p$, V_p , V_s are the ground velocities of correspondingly compressional and shear waves.

Coefficients C_3, C_4, \dots are small enough to neglect by the other components of series (5). Note, that for values C_0, C_1, C_2 the ground parameters have the critical influence at the depths down to $z \approx r_0$. For example, if at the depth $z = 2r_0$ there is a perfectly rigid medium, then its influence on stiffness K_{gr} will be negligible.

Applications of obtained formulas

Further, we shall consider several designs of the source. We start from seismic prospecting vibrator. In seismic prospecting vibrators, where the working frequency band starts from about 10 Hz, the chosen resonant frequency f_{pr} of the load is about 2 - 3 Hz. Therefore, in a working frequency band the loading mass is well decoupled from vibration and we can take $Z_{pr} = 0$. In this case

$$Z_s = Z_{pl} + Z_{gr} = pM_{pl} + pM_{gr} + (1/p)K_{gr} + R_{gr} = (1/p)K_{gr} [1 - (f/f_{plg})^2 + ja_{plg}(f/f_{plg})], \quad (9).$$

Ground impedance has the form

$$Z_{gr} = pM_{gr} + (1/p)K_{gr} + R_{gr} =$$

$$= (1/p)K_{gr} [1 - (f/f_{gr})^2 + ja_{plg}(f/f_{gr})], \quad (10)$$

$$\omega_{gr}^2 = K_{gr}/M_{gr}; \omega_{plg}^2 = K_{gr}/M_{plg}; M_{plg} = M_{pl} + M_{gr}, \quad a_{plg} = R_{gr}(\omega_{plg}M_{plg})^{-1}, \quad (11)$$

which leads to the final formulas

$$-F_{gr} = F_0 Z_{gr}/Z_s, \quad J_{pl} = F_0 Z_s^{-1}, \quad (12)$$

To be concrete, we consider the vibrator with vibroplatform area $S_{pl} = 2 \text{ m}^2$, the inertial mass $M_i = 1,800 \text{ kg}$, where the total vibroplatform mass $M_{pl} = 2,000 \text{ kg}$, and force amplitude of the force chamber $F_0^0 = F_i = 10^5 \text{ N} = 10 \text{ ton}$ in 10 to 200 Hz frequency range.

Let us evaluate the "adjoin mass" M_{gr} of such vibrator. For a source with round shaped contact area $S_{pl} = \pi r_0^2$ we have Equation (8). Taking $S_{pl} = \pi r_0^2 = 2 \text{ m}^2$, we find that $r_0 = 0.8 \text{ m}$, and $r_0^3 = 0.31 \text{ m}^3$. Let the ground be a Poisson's medium, and, therefore, $\gamma^2 = 1/3$. Density of the ground is equal to $\rho_{gr} = 1.7 \cdot 10^3 \text{ kg/m}^3$. Then, $M_{gr} \approx 600 \text{ kg}$. For the stiffness K_{gr} of the ground we have (6). First, let us find an approximate value of K_{gr} using experimental data.

Road engineers, which use the vibrators for soil compaction, take area size $S_{pl} = (1-2) \text{ m}^2$ for platform mass $M_{pl} \approx (2-3) \cdot 10^3 \text{ kg}$. Then, the frequency $f_{plg} \approx 18-20 \text{ Hz}$. As the soil gets more compacted, or for stiff soils, this frequency can reach up to 40 Hz. Therefore, if we take an "average" soil, where $S_{pl} = 2 \text{ m}^2$, $M_{pl} = 2 \cdot 10^3 \text{ kg}$, the resonance frequency $f_{plg} \approx 30 \text{ Hz}$. It means that $M_{plg} = M_{pl} + M_{gr} = 2.6 \cdot 10^3 \text{ kg}$, and $K_{gr} = \omega_{plg}^2 M_{plg} = 9.36 \cdot 10^7 \text{ kg/s}^2$.

It is interesting, which homogeneous half-space corresponds to such stiffness? Substituting values ρ_{gr} , r_0 , and $\gamma^2 = 1/3$ in Equation (6) we obtain $V_s^2 = 1.7 \cdot 10^4 \text{ m/s}$, $V_s = 130 \text{ m/s}$. Why are these values so small? As it was mentioned above, for the stiffness K_{gr} , the ground parameters have the main influence at depths shallower than $z \approx r_0$. For such depths in soft soils, the value V_s can be as small as 70 m/s. After substitution of values $r_0 = 0.8 \text{ m}$, $\gamma^2 = 1/3$, $V_s = 130 \text{ m/s}$ in Equation (7) we obtain $R_{gr} = 3.6 \cdot 10^5 \text{ kg/s}$. Hence, $a_{plg} = 0.73$. Force, acting on the ground at resonance frequency (when $x_{plx} = 1$) will be $|F_{gr}| = F_i \cdot 1.42 = 10 \cdot 1.42 = 14.2 \text{ tons}$.

Displacement amplitude of the vibroplatform can be found using Equation (12). Substituting $F_i = 10 \cdot 10^4 \text{ N} = 10 \text{ tons}$, $K_{gr} = 7.56 \cdot 10^7$, $a_{plg} = 0.73$ in this equation we obtain $U_{gr} \approx 10^{-3} \text{ m}$.

Power of emitted elastic waves will be $W = (1/2)R_{gr}J_{gr}^2 = 13.5 \cdot 10^3 = 13.5 \text{ kW}$, (13).

This result is close to the experimental measurement for hydraulic vibrator ($W = 15 \text{ kW}$). For $a_{plg} = 1$, at frequencies $f/f_{plg} = 1/3, 2/3, 1, 2, 3, 4, 5$ we have correspondent values.

$$F_{gr}/F_i = 1.078; 1.26; 1.22, 0.55, 0.39, 0.34, 0.32.$$

For $a_{plg} = 1/4$ at same frequencies we have

$$F_{gr}/F_i = 1.086, 1.53, 3.03, 0.17, 0.21, 0.24, 0.26.$$

In all above evaluations we neglected by the oscillation of the loading mass. Now, let us consider, when and how such assumption is accurate.

Displacement amplitude of the loading mass is given by Equation (5). For $a_{pr} = 0.5$, and at frequencies $f/f_{pr} = x_{pr}$, $x_{pr} = 1, 2, 4, 8$ the ratio J_{pr}/J_{pl} is equal to 2.2, 1/2.3, 1/6.8, 1/15.

For $a_{pr} = 0.1$ at same frequencies this ratio $J_{pr}/J_{pl} = 10, 1/10, 1/14, 1/30$. How large can be a_{pr} in reality? Our model has just one loading mass M_{pr} , which is supported by a spring with stiffness K_{pr} . In practice, there are many loading masses. These masses are uncoupled from vibrations by springs of a various kind. If any pair "mass and spring" has small attenuation, it will affect the end of vibration when frequency approaches zero and passes frequency f_{pr} . A significant beating will occur then. Practically, the special precautions are made and attenuation coefficient is kept at the range $a_{pr} \geq 0.5$.

About the 100-ton low-frequency vibrator

Let us see, how the 100-ton vibrator obeys the above formulas. We take the familiar average soil with parameters $V_s = 130 \text{ m/s}$, $\gamma^2 = 1/3$, $\rho_{gr} = 1.7 \cdot 10^3 \text{ kg/m}^3$. The basic vibrator parameters are: vibroplatform area $S_{pl} = 16 \text{ m}^2$, the total vibroplatform mass $M_{pl} = 120 \cdot 10^3 \text{ kg}$, force amplitude of the force chamber changes according to the law $F_i = \omega^2 U_i^0 M_i$, and at frequency of 10 Hz is equal to $100 \cdot 10^4 \text{ N} = 100 \text{ tons}$. Substituting these values in Equations (1) - (12), we obtain $r_0 = 2.26 \text{ m}$, $M_{gr} \approx 13 \cdot 10^3 \text{ kg}$, $M_{plg} = M_{pl} + M_{gr} = 133 \cdot 10^3 \text{ kg}$, $K_{gr} \approx 1.5 \cdot 10^4 V_s^2 = 2.5 \cdot 10^8$, $f_{plg} = 6.9 \text{ Hz}$, $a_{plg} = 0.496$. Force F_i at frequency 10 Hz is equal 100 tons. At frequency 6.9 Hz the force is equal $F_i = 47.6 \text{ tons}$. Force, acting on the ground at resonance frequency (for $x_{plx} = 1$),

is $|F_{gr}| = 98.6$ tons. Amplitude of vibroplatform displacement at $x_{p|g}=1$ is $U_{gr} \approx 3.8$ mm., while the power is $W=38.7$ kW

Let us find those values at upper frequency of 10 Hz., where $F_i=100$ tons, $x_{p|g} = 10/6.9 = 1.45$. Force, acting on the ground will be $F_{gr} = 81$ tons, with displacement amplitude of the vibroplatform (ground) of $U_{gr}^0 \approx 3$ mm., and power of emitted elastic waves -- $W=50$ kW. Actual measurements are closely agree with these results.

Integrity Structures Testing

Vibro seismic monitoring of engineering constructions is needed for tracking changes of durability in elements of a construction during its operation. This problem is proposed to be solved by recording of the construction oscillations which are generated by a remotely placed low-frequency vibrator. The recorded oscillations will be transformed in pulse seismograms. The response the construction elements on vertical (horizontal) displacements can be determined from the signals generated by longitudinal (shear) waves. Using the differences in displacements of the adjacent points of the construction a map of relative deformations can be found. In linear approximation this map can be transformed into an assessment strength map for elements of the investigated construction. The vibroseismic monitoring consists of repeated registration of vibroseismic oscillations from a remote source. The monitoring sessions should be done after changes in the construction equipment arrangement. It is supposed that the buildings are the nuclear reactor and storehouse of nuclear waste, which will be the typical application examples of the proposed technology. For diagnostics of engineering structures physical state we also use microseisms. It will be discussed in the other report. These two methods complement each other. The data show that in oscillations of large constructions the flexural types of motion are dominating. Therefore, for understanding and interpretation of data the properties of flexural oscillations and waves are used [4].

Conclusions

How large should be a vibrator capable to illuminate Russian Far East including Japan Islands, which covers the area with radius of 2,000-3,000 km? There are graphycs showing an amplitude of P-wave as a function of epicenter distance. Such graphycs were compiled in the Institute of Earth Physics of the Academy of Sciences of the USSR by processing and generalization of seismological data (see Figure 6). These results show that P-wave amplitudes decay 5-8 times in the interval 300 - 700~km. It follows that in order to achieve a signal/noise ratio comparable to that in the seismograms in Figure 1, it will be necessary to use a vibrator of amplitude 500 - 800~tons for an hour. In this case, the depths up to 200~km will be illuminated. In order to get a seismogram at a distance of 3,000~km, a 3~Kton force amplitude is required. We have designed a vibrator of the kiloton class and built a laboratory prototype of it, but this project was not realized due to disintegration of the USSR

Finally we would like to note the following. We are certain that the future of seismic active monitoring belongs to eccentric vibrators. The predecessor of powerful low-frequency vibrators was the eccentric vibrator " Vibrolocator " intended for seismic prospecting of oil and gas deposits using compressional and shear waves. It had amplitude of force about 10 tons in a frequency range from 10 up to 70 Hz. Its force could be oriented in vertical and horizontal directions. Cost of " Vibrolocator " is 5 - 10 times less in comparison with vibrators of system " Vibroseis".

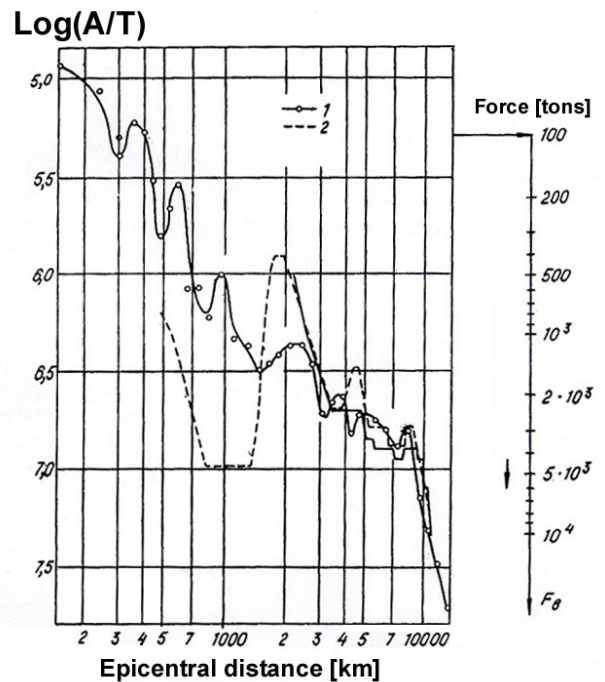


Figure 6. Amplitude of the direct P- wave vs epicentral distance.

(1) Data from the Institute of the Physics of the Earth Academy of Sciences of USSR; (2) Data from USGS. Right vertical scale shows the ground vibrator force needed for recording of seismograms similar to those of Figure-1. This scale shows that if we need a 300~km distance for a 100-ton vibrator, then for the same quality of data and vibro-session duration at 10,000~km distance we need a vibrator with 10~Kton force amplitude.

In 1989 - 90 the US Texaco Exploration and Production Technology Division (Texaco-EPTD) have intended to adjust and manufacture of " Vibrolocator " in the USA. Under the initiative of Tom Russell from this company in Texas, the comparative tests of " Vibrolocator " with hydraulic vibrator " Y-2400 " of system " Vibroseis " have been carried out. Tests have shown, that these vibrators give seismic sections of identical quality for vertical excitation. Comparative tests at horizontal orientations of force of vibrators were not done as at that time in the USA yet there were no horizontal vibrators.

On the part of Soviet Union this business was conducted by the Ministry of Geology of the USSR. But as soon the USSR has collapsed, this project was abandoned. Now, the State Duma of Russia considers the laws facilitating joint collaboration of Russian and foreign scientists. If these laws really appear, then it is quite possible that such machine as "Vibrolocator", will find an interest among foreign businesses and academia.

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