12. *The Velocity of Elastic Waves in Sand.*

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1. Introduction.

In our previous papers[1] we discussed the elastic properties of certain kinds of soil by subjecting them vibration. From our previous investigations[2] it was found that the elastic properties of soils differ with the kind of soil, the natural and the recomposed states, and the moisture content, etc. To apply our findings, not only to geophysical problems, such as the propagation of seismic waves, especially in the superficial layer of the earth's crust, but to civil engineering problems as well, it was found desirable to make further experiments with as large a variety of sands and soils as possible.

The object of this study is to ascertain the properties of sand in connexion with these subjects, and to develope the dynamics of granular substances like sand.

Some of the properties of sand have already been studied in Japan by T. Terada and N. Miyabe[3], namely the deformation of sand masses. They applied the results of their experiments to geophysical phenomena, such as chronic deformations of the earth's crust. Recently K. Takahasi[4], who studied the dynamical behaviour of a granular mass, found that there are two kinds of modes in the sand flow, similar to such natural phenomena as snow slides and land slides. In the field of civil engineering, some of the mechanical properties of sand such as porosity, shearing strength, etc. have received the attention of investigators[5],

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1) M. ISHIMOTO and K. IIDA, *Bull. Earthq. Res. Inst.*, **14** (1936), 632; **15** (1937), 67.
K. IIDA, *Bull. Earthq. Res. Inst.*, **15** (1937), 828.

2) M. ISHIMOTO and K. IIDA, *loc. cit.*, 1).

3) T. TERADA and N. MIYABE, *Bull. Earthq. Res. Inst.*, **4** (1928), 33; **6** (1929), 109; **7** (1929), 65.
N. MIYABE, *Bull. Earthq. Res. Inst.*, **12** (1934), 195; **14** (1936), 553.

4) K. TAKAHASI, *Geophys. Mag.*, **11** (1937), 165.

5) T. WATANABE, *Bull. Geotechnical Committee, Government Railways*, **4** (1936), 176.
N. YAMAGUTI, *ibid.*, **4** (1936), 158, (in Japanese).
R. ONO and K. MANAI, *Journ. Civ. Eng. Soc.*, **22** (1936), 591, (in Japanese).

with the result that some of their mechanical properties are now fairly well known.

But as we are still ignorant how these substances will be affected by elastic waves, in the present experiments we first tried to subject sand to elastic waves in order to ascertain whether or not sand possesses any elastic properties, and also to know whether or not the relations between these properties and the kind of sand, its closeness of packing, and moisture content are similar to those ascertained for soils.

2. Mechanical Analysis of Sands.

Four kinds of sand were experimented with. These are shown in Fig. 1.

As the size of the sand grains has an important bearing upon its physical properties, we used sieves of Tyler's standard type as adopted by the U. S. Bureau of Standards. The experiments were conducted in the laboratory of the Geotechnical Committee, Government Railways of Japan. The methods of mechanical analysis are exactly the same as those described in Watanabe's paper[6]. The water is first removed from the sand, and the sand then passed through a series of Tyler's

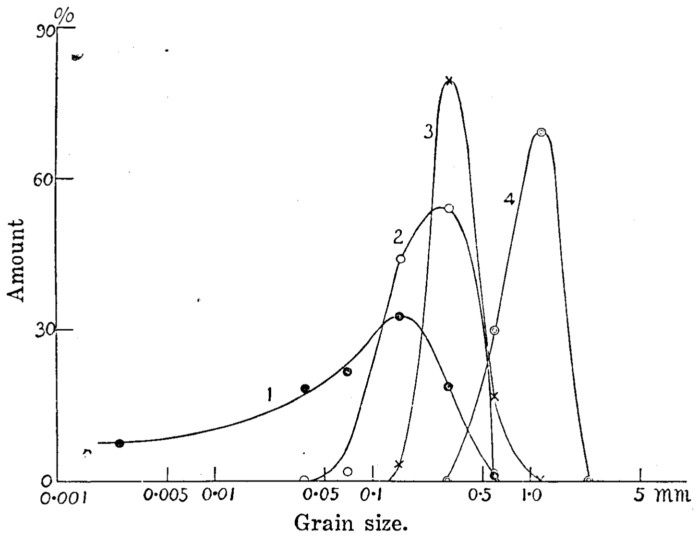

Fig. 2. Frequency curves of sizes of sand grains.
● Sand No. 1. ○ Sand No. 2.
× Sand No. 3. ◎ Sand No. 4.

standard sieves mounted on a shaking machine and shaken for 15

6) T. WATANABE, *loc. cit.*, 5).

Table I. Mechanical Analysis of Sand.

Kinds of sand No.	Mesh number (Tyler's standard sieves) 8 grain size 2·36 mm	14 grain size 1·17 mm	28 grain size 0·59 mm	48 grain size 0·30 mm	100 grain size 0·15 mm	200 grain size 0·07 mm	Silt grain size 0·07∼0·005 mm	Clay grain size 0·005∼0 mm	True density
	%	%	%	%	%	%	%	%	
1	0	0	1·08	18·70	32·98	21·58	18·22	7·44	2·825
2	0	0	0·02	54·36	44·02	1·58	0·02	0	2·732
3	0	0·08	16·92	79·96	3·04	0	0	0	2·660
4	0·16	69·84	29·98	0·02	0	0	0	0	2·746

minutes, so that the grains are duly separated. The results are shown in Table I and Fig. 2.

The resulting sand was then classified into four kinds, Nos. 1∼4, No. 1 being the finest and No. 4 the coarsest. As will be seen from the figure, the frequency curves of these sands differ. The frequency curves of Nos. 2, 3, 4 are sharp, while that of No. 1 is comparatively gentle. Upon classifying these sands according to their constituent minerals, No. 1 differs from the other three kinds in containing chiefly sediments derived from metallurgical slags, while the remainder are river sand containing chiefly quartz.

3. Variation in Sand Density with Moisture Content.

Since as already shown in Table I, the true densities of sand range from about 2·66 to 2·83, the differences between them are not great. At any rate, the density of sand No. 1 exceeds that of all the others, although their bulk densities vary with the water contained in them. Moreover the variations in densities seem to differ also with the kind of sand.

In order to observe the variation in sand density with moisture content, the specimens were first weighed in their moist state, after which they were gradually dried. We then measured their volumes and weighed them in their moist condition (weights of the sand grains and of the moisture),

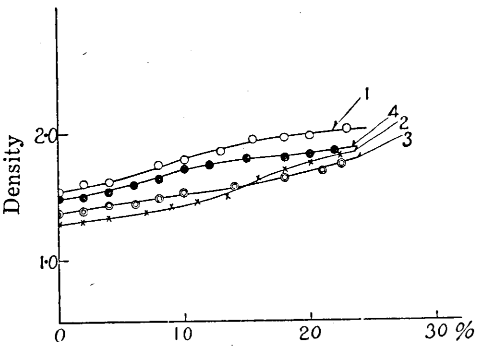

Fig. 3. Relation between the density and the moisture content. The numbers in the figure correspond to that of the kind of sand.

Table II. Bulk Density and Moisture Content of Sand.

Sand No. 1		Sand No. 2		Sand No. 3		Sand No. 4	
Moisture content	Density	Moisture content	Density	Moisture content	Density	Moisture content	Density
0	1·54	0	1·28	0	1·37	0	1·49
2·1	1·60	2·2	1·30	2·2	1·38	2·4	1·50
4·2	1·62	4·1	1·34	4·3	1·44	4·2	1·54
8·1	1·75	7·3	1·37	6·2	1·44	6·1	1·59
10·4	1·79	9·2	1·43	8·1	1·48	8·2	1·64
13·3	1·85	10·8	1·46	9·9	1·53	10·3	1·73
15·5	1·95	13·4	1·48	13·9	1·58	12·1	1·75
18·2	1·96	15·9	1·64	18·0	1·66	15·0	1·80
20·0	1·99	18·1	1·70	21·2	1·69	18·3	1·79
22·9	2·01	20·0	1·75	22·4	1·77	20·0	1·83
		22·4	1·81			22·0	1·84

and calculated their densities ρ from the ratio of their weights to their volumes. These are shown in Table II. The densities were plotted as ordinates and the moisture contents as abscissae, as shown in Fig. 3. As will be seen from this figure, the density seems slightly to increase with increase in moisture content. However it was found that when the moisture content exceeded 10 per cent, the density of No. 2 or 3 rapidly rose. This was more the case with No. 2 than any other. When the moisture content exceeded 16 per cent, the rise in density of No. 1 or 4 became almost constant.

As is well known, although it is possible to make a ball of sand only when it is moderately wet, it is impossible to do so when it contains much more water. The approximate moisture limits for making sand balls are shown in Table III.

Table III. Moisture Content that Sand Flow takes place.

Kind of sand	No. 1	No. 2	No. 3	No. 4
Moisture content	23·75%	24·6%	22·5%	9·9

4. Experiments.

(*a*) *Methods.* In the present experiments, both apparatus and methods were the same as those employed previously. The forms of the sand specimens were cylinders of initial heights of from 20 to 30 cm and the diameter about 5 cm.

With moderately wet sand, balls could be made, while with dry and very moist sand it could not be done, so that for the latter suitable devices for making the sand-cylinders had to be contrived. Since a receptacle in which to hold the sand is necessary, and since this receptacle must be of a substance that will not affect the properties of the sand in question, cellophane was selected to hold the sand. For reasons to be given later, the effect of the cellophane-tube holding the sand in the experiment is practically negligible. Thus in some cases of dry and very wet sands, we experimented with the sand packed in the cellophane-tube. In the case of moderately wet sand, we used brass moulds and packed the sands into them, and then extracted the sand-cylinder from the moulds.

These sand specimens were then set on the vibrating plate of our apparatus, a schematic diagram of which is shown in Fig. 4. In this figure m is a magnet, M a small lens mirror attached to pivot P. As already described in our previous papers, these serve to magnify the vibration amplitude of the top of the sand column. V is the vibrating plate for vibrating the specimen. Photographic records were made while applying forced transverse and longitudinal vibrations to the specimen up to the limit of vibration frequency. We could then find the resonance frequency of its vibration, after which we computed both the transverse and the longitudinal wave-velocities in the specimen.

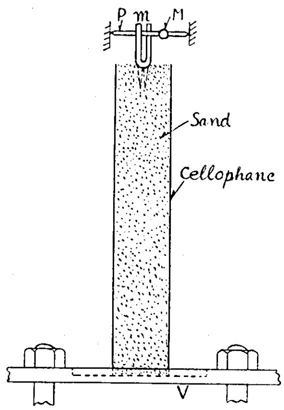

Fig. 4. Schematic diagram showing the arrangement of the longitudinal vibrating system.
P: pivot. m: magnet.
M: small lens mirror.
V: vibrating plate.

(*b*) *Methods of packing the sand.* As the closeness with which the sand grains are packed is an important factor in the propagation of elastic waves, the experiments were made with each of the sands both closely and loosely packed. In order to pack as closely as possible, the cylinder, which contained sand grains up to a height of 15 cm, was allowed to drop by withdrawing our hand from it.

Then as the cylinder droped the sand particles in the cylinder settled down, and the height of the sand-cylinder diminished with the number of times the cylinder was allowed to drop. The results of this treatment are shown in Fig. 5, in which the amounts of the fall in height are plotted against the number of times it was dropped. As will be seen from the figure, after it has been dropped five times, the height of the sand-cylinder becomes almost constant. To ensure densest packing, the same cylinder was also subjected to vibration, when its height diminished by about 1∼2 per cent. For example, in the case of dry sands, we investigated that the porosity of sand No. 3 varies from about 49 per cent to about 41 per cent, and that of sand No. 4 from about 46 per cent to about 40 per cent. To observe the relation between the denseness of packing and the velocity through the sand, the experiments included sand both closely and loosely packed, detailed results of which will be given later.

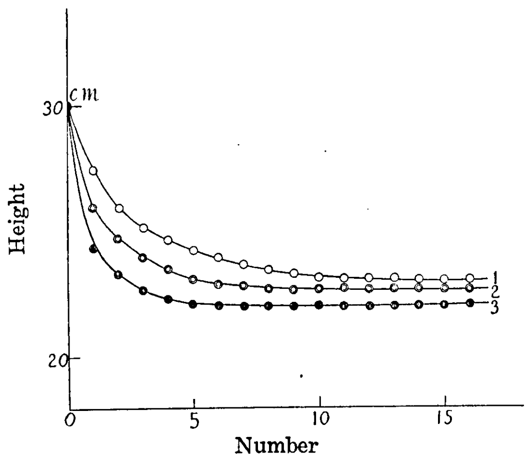

Fig. 5. Relation between the height of sand-cylinder and the number of times the cylinder was allowed to drop. 1, dry sand No. 1. 2, wet sand No. 2. 3, wet sand No. 4.

(c) *The effect of the cellophane boundary wall.* It is evident that the effect on the experiment of the boundary wall of the cellophane-cylinder holding the sand should also be considered. To determine the effect we used cellophane-cylinders of various diameters; as shown in Table IV. In Fig. 6, the curves showing the relation between the resonance frequency and the diameter are drawn for dry sand No. 4 and wet sand No. 2, the latter being considered from appearances to be in the fluid state. As will be seen from the curves in Fig. 6, the resonance frequencies of vibration are independent of the diameter of the cellophane-cylinder, from which it

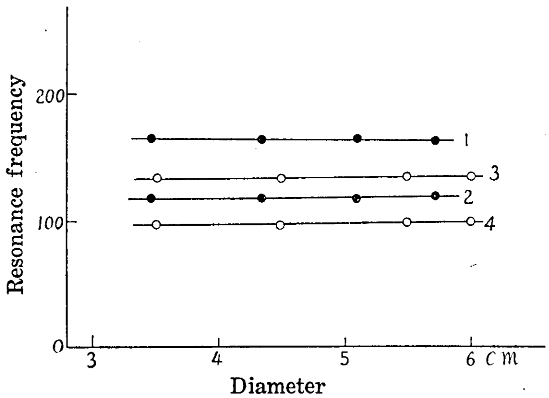

Fig. 6. Relation between the resonance frequency of vibration and the diameter of cellophane-cylinder.
● Dry sand No. 4. ○ Wet sand No. 2 with moisture content 19·4%. 1, 3 show the case of longitudinal vibration. 2, 4 show the case of transverse vibration.

Table IV. Resonance Frequencies and Diameters of Cellophane-cylinder.

(Nl: longitudinal resonance frequency; Nt: transverse resonance frequency.)

Sand No. 2			Sand No. 4		
Dia.	Nl	Nt	Dia.	Nl	Nt
3·52	135	98	3·47	166	118
4·49	134	97	4·34	166	118
5·49	136	100	5·10	165	119
6·00	136	100	5·72	164	120

will seem that the effect of the boundary wall is practically negligible so far as the present experiments are concerned. We may, therefore, extend the results of our experiment to the case of no boundary wall. We may say that the resonance frequencies obtained in our experiments are those of the sand column itself without the effect of the cellophane-boundary wall.

5. Results of the Experiments.

(*a*) *Determination of two kinds of wave-velocities.* With the same methods that were described in our previous papers, we determined two kinds of elastic wave-velocities: the longitudinal and the torsional. An example of a diagram showing the relation between the fundamental resonance periods T_l, T_t and the height of the sand column, h, may be seen in Fig. 7, in which the period, T_l or T_t is taken as ordinate and the height h as abscissa. The figures are the reducing curves, by which the two kinds of wave-velocities are determined. The values thus obtained in each kind of sand are shown in Table V. To observe the effect of moisture content on the physical properties

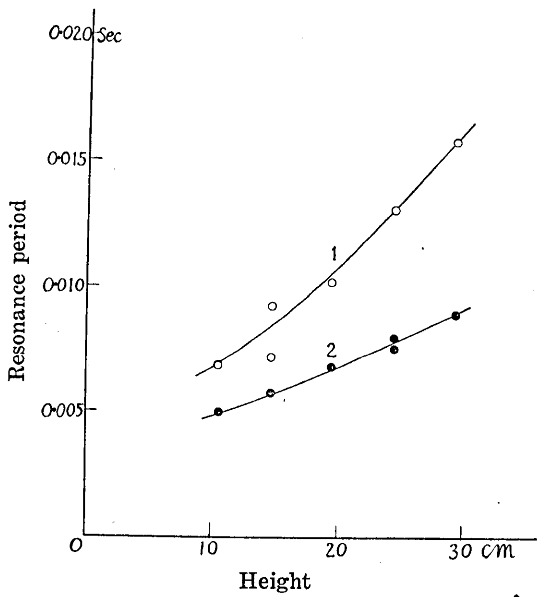

Fig. 7. Relation between the resonance period of vibration and the height of sand-cylinder. Specimen: wet sand No. 3, $w=14·8\%$.
1, the case of torsional vibration.
2, the case of longitudinal vibration.

Table V. Longitudinal and Transverse Wave-velocities, Densities, and Moisture Content.

* Made with a cellophane-cylinder.

Sand No. 1					Sand No. 2					Sand No. 3					Sand No. 4				
w (%)	ρ $\left(\frac{gr}{cm^3}\right)$	V_l $\left(\frac{m}{sec}\right)$	V_t $\left(\frac{m}{sec}\right)$	V_l/V_t	w (%)	ρ $\left(\frac{gr}{cm^3}\right)$	V_l $\left(\frac{m}{sec}\right)$	V_t $\left(\frac{m}{sec}\right)$	V_l/V_t	w (%)	ρ $\left(\frac{gr}{cm^3}\right)$	V_l $\left(\frac{m}{sec}\right)$	V_t $\left(\frac{m}{sec}\right)$	V_l/V_t	w (%)	ρ $\left(\frac{gr}{cm^3}\right)$	V_l $\left(\frac{m}{sec}\right)$	V_t $\left(\frac{m}{sec}\right)$	V_l/V_t
0	1·76	200	117	1·71	1·9	1·30	202*	124*	1·63	4·1	1·43	180*	109*	1·65	0	1·49	163*	100*	1·63
3·1	1·78	171	105	1·63	6·0	1·35	190	115	1·65	7·2	1·46	170	103	1·65	2·1	1·50	160*	98*	1·63
5·3	1·79	162	99	1·64	9·9	1·45	178	107	1·66	10·9	1·56	148	89	1·66	4·2	1·54	148*	90*	1·64
8·2	1·80	166	101	1·64	14·2	1·59	160	95	1·68	14·0	1·58	135	81	1·67	6·9	1·59	140*	85*	1·65
10·6	1·83	170	102	1·67	18·3	1·70	136	79	1·71	14·8	1·60	133	78	1·71	9·8	1·72	120*	72*	1·67
11·7	1·86	161	96	1·68	20·0	1·75	130*	75*	1·73	17·0	1·63	116*	68*	1·71	12·3	1·74	117*	70*	1·67
14·5	1·89	143	83	1·72	21·8	1·77	140*	50*	2·80	20·1	1·67	96*	56*	1·71	13·9	1·76	100*	61*	1·61
17·6	1·92	94	54	1·74	24·0	1·80	147*	25*	5·88	22·9	1·78	92*	53*	1·74	18·0	1·79	80*	47*	1·70
19·3	1·99	95*	47*	2·02															
22·8	1·79	160*	12*	13·33															
24·0	1·70	200*	8*	25·00															

of sand, we plotted the wave-velocities obtained by the experiments against the moisture content, as shown in Figs. 8~9, in which we always took the moisture content as abscissa and the velocities as ordinate. In the experiments for determining these moisture relations, we sometimes used sand columns in the form of cellophane-cylinders and other times in the form of the sand-cylinder itself.

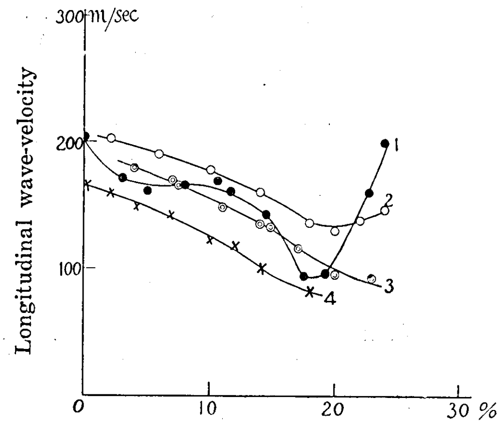

Fig. 8. Relation between the longitudinal wave-velocity and the moisture content.
1, sand No. 1. 2, sand No. 2.
3, sand No. 3. 4, sand No. 4.

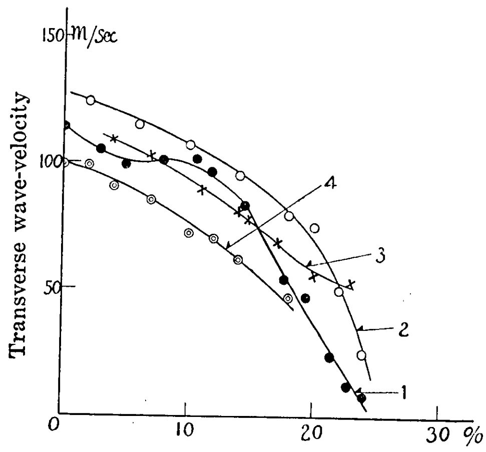

Fig. 9. Relation between the transverse wave-velocity and the moisture content.
1, sand No. 1. 2, sand No. 2.
3, sand No. 3. 4, sand No. 4.

As will be seen from these figures, the transverse wave-velocities, V_t, of these sands decrease somewhat rapidly with increase in moisture content, though the manner in which they do so differs with the particular kind of sand. Their longitudinal wave-velocities, V_l also decrease with increase in moisture content within the range of about 0~19 per cent of moisture, whereas those of sand Nos. 1 and 2 increase with moisture content below 19 per cent. Furthermore, in the case of sand No. 1, the relation between the longitudinal and the transverse wave-velocities and the moisture content fluctuated as shown in Figs. 8~9. As to the main reason for the fluctuation, it is believed that still finer grained particles or some adherent colloidal particles are introduced into the kind of sand, such as No. 1, and these adherent particles undoubtedly greatly affect its elastic properties. It seems that thixotropic phenomena may occur as the result of these colloidal particles. Further in the case of finer sands, such as Nos. 1 and 2, it was observed that their longitudinal wave-velocities seem to increase with increase in moisture content exceeded 20 per cent, while their transverse wave-velocities become too small for detection. These sands may be in the transition state from solid to liquid or to viscous fluid. Such phenomena may not be observed in coarse sand like No. 4.

(*b*) *Variation in velocity with deneseness of packing.* Since as just mentioned, the closeness with which the sand grains are packed is an important factor affecting its elastic properties, we experimented with sand in various states of packings (Table VI). In order to determine the relation of the velocity to closeness of packing, we plotted

Table VI. Longitudinal and Transverse Wave-velocities, Porosities, and Densities.

Sand No. 1 (w=15%)				Sand No. 3 (w=12%)				Sand No. 3 (w=5%)			
ρ	P (%)	V_l (m/sec)	V_t (m/sec)	ρ	P (%)	V_l (m/sec)	V_t (m/sec)	ρ	P (%)	V_l (m/sec)	V_t (m/sec)
1·78	46·5	95	55	1·51	50·1	86	50	1·42	49·2	130	80
1·79	46·2	98	56	1·53	49·4	91	55	1·47	47·6	138	84
1·80	45·9	97	55	1·60	47·1	113	65	1·49	46·9	145	89
1·83	45·0	103	58	1·63	46·2	118	69	1·51	46·1	148	90
1·86	44·1	113	65	1·66	45·1	130	75	1·52	45·8	152	94
1·87	43·8	112	64	1·68	44·4	135	78	1·54	45·1	152	93
1·90	42·9	112	64	1·70	43·9	141	80	1·57	44·0	158	98
1·95	41·4	122	71	1·71	43·5	144	84	1·60	42·9	170	105
1·99	40·2	136	80								

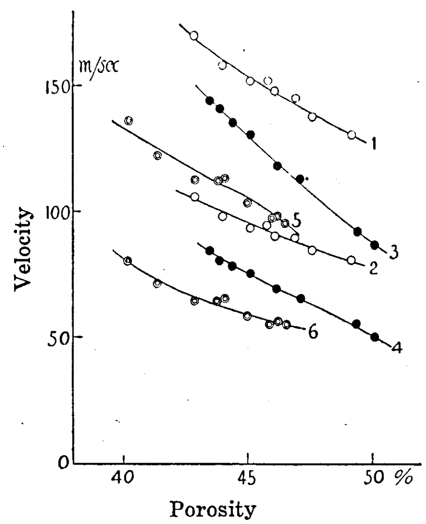

Fig. 10. Showing the relation of the velocity to closeness of packing.
● sand No. 3; moisture content w= 12%.
○ sand No. 3; w=5%.
◎ sand No. 1; w=15%.
1, 3, 5; the case of longitudinal vibration.
2, 4, 6; the case of torsional vibration.

the velocities as ordinates and the corresponding porosities of the sand as abscissae, as shown in Fig. 10, in which porosity P, in percentage, is calculated from the true density and the bulk density, that is

$$P=100-\frac{\rho}{\rho_s}(100-w), \tag{1}$$

where ρ_s is the true density, ρ the bulk density corresponding to the moisture content w per cent. As will be seen from Fig. 10, the velocities vary with the closeness of packing and seem to increase with diminishing porosity as a linear function of it. The curves of No. 1, 2, 3, 4, seen in the figure, are for the same kinds of sand as No. 3, and the curves of No. 5, 6 for the other kind of sand as No. 1. We see that the relations between the velocities and the porosities in the case of moist sand fluctuate somewhat more than those in the case of dry sand. We also noticed that this relation in the case of sand No. 1 fluctuates, which it seems, is partly due to its constituent particles, as already hinted.

6. Remarks.

As already explained in the preceding section, the elastic properties of sand are greatly affected by colloidal matters and the water contained in them. We noticed that in every kind of sand, the ratio of V_l/V_t increases with the moisture content, especially the finer grained sands, such as No. 1 and No. 2. When the moisture content in the finer grained sands, exceeds about 20 per cent, V_l increases somewhat rapidly, while V_t diminishes to such an extent as to be scarcely observable. When the water in sand is increased very much more, V_l seems to approach the velocity of sound in liquid. Consequently, sand in such a state behaves like a liquid. Therefore, it will be seen that there are two states in sand, according to their moisture contents. Since elastic waves propagate through sand, it is probably only natural that sand should possess elastic constants. It may be necessary to determine these elastic constants, although it may not be possible to do so from the theory of elasticity; its procedure will nevertheless be difficult in practice. It has never been shown that sand is fully governed by the condition required by the elastic theory. The assumption that the formulae of elastic theory can be applied to sand requires experimental justification. Although the exact mechanism by which the elastic waves propagate in sand seems to be still wrapped in mystery, we wished to know the elastic constants of sand from formulae similar to those of the elastic theory. We concluded, therebore, that the sand-cylinder

Table VII. E', μ', and σ'.

Sand No. 1				Sand No. 2				Sand No. 3				Sand No. 4			
w (%)	E' (c.g.s.)	μ' (c.g.s.)	σ'	w (%)	E' (c.g.s.)	μ' (c.g.s.)	σ'	w (%)	E' (c.g.s.)	μ' (c.g.s.)	σ'	w (%)	E' (c.g.s.)	μ' (c.g.s.)	σ'
0	$\times 10^8$ 7·04	$\times 10^8$ 2·41	0·46	1·9	$\times 10^8$ 5·25	$\times 10^8$ 2·00	0·31	4·1	$\times 10^8$ 4·64	$\times 10^8$ 1·70	0·36	0	$\times 10^8$ 3·96	$\times 10^8$ 1·49	0·33
3·1	5·20	1·96	0·33	6·0	4·88	1·79	0·36	7·2	4·22	1·55	0·36	2·1	3·84	1·44	0·33
5·3	4·69	1·75	0·34	9·9	4·59	1·66	0·38	10·9	3·42	1·24	0·38	4·2	3·38	1·25	0·35
8·2	4·96	1·83	0·36	14·2	4·07	1·44	0·41	14·0	2·88	1·04	0·38	6·9	3·12	1·15	0·36
10·6	5·29	1·90	0·39	18·3	3·14	1·07	0·47	14·8	2·83	0·97	0·46	9·8	2·48	0·89	0·39
11·7	4·82	1·72	0·40					17·0	2·19	0·76	0·44	12·3	2·38	0·85	0·40
14·5	3·86	1·32	0·46					20·1	1·54	0·52	0·48	13·9	1·76	0·66	0·33
17·6	1·68	0·56	0·49									18·0	1·15	0·39	0·47

would behave like an elastic solid, and assumed that the relations between the velocities and the elastic constants of sand at moisture content ranging from about 0 to 18 per cent are given by

$$\left.\begin{aligned} V_l=\sqrt{\frac{E'}{\rho}},\quad V_t=\sqrt{\frac{\mu'}{\rho}}, \\ \sigma'=\frac{1}{2}\left(\frac{E'}{\mu'}-2\right), \end{aligned}\right\} \qquad (2)$$

where E', μ', σ' are the elastic constants similar to Young's modulus, modulus of rigidity, and Poisson's ratio respectively, and ρ the bulk density. The values derived from Table VI by equation (2) are given in Table VII.

The values for the coefficients, such as E', μ' obtained these methods are of the order of 10^8 in c.g.s. units at moisture content ranging from about 0 to about 10 per cent. These magnitudes are comparable with those of soils given by the foregoing investigations.

7. Summary and Conclusion.

We investigated the velocities of elastic waves in four kinds of sand. The relation between density and moisture content was also studied. The velocities of elastic waves in sand were obtained by means of the vibration method. Moreover, we succeeded in ascertaining the elastic wave-velocities of granular substances, such as sand, by using cellophane. It was ascertained that the elastic properties are greatly affected by the closeness of packing, the moisture content, and the presence of adherent colloidal particles in the sand. The velocities decrease with increase in moisture content or with increase in porosity. The transverse wave-velocities decrease somewhat rapidly with increase of moisture content, while the longitudinal wave-velocities of some sands increase with moisture content exceeded 19 per cent. We were thus able to observe the transitional state of sand from the ordinary solid state to the liquid state by virtue of the increasing water in the sand.

The velocities through the finer grained sands seem to be greater than those through the coarse grained sands.

Finally, the elastic constants of the sands were determined by the assumption that formulae similar to that of the elastic theory could be applied.

These studies on the properties of granular substances are being continued, and the results will be discussed a future issue of the Bulletin.

In conclusion, my sincerest thanks are due to Professor Mishio Ishimoto for his kind guidance and encouragement, and also to Dr. T. Watanabe, by whose kind guidance the mechanical analysis of the sands which were used in the present experiments was carried out.

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12. 砂の中を傳播する彈性波の速度

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此の論文には砂の彈性的性質，特に砂の如き粒狀構造物體の中を傳播する彈性波の速度に就いて實驗した結果が述べてある．此の研究は今迄しばしば述べた如き物質の彈性的性質に對する研究の續きである．

實驗には粒徑の異つた4種類の砂を選んだ．今回の實驗方法は前回と全く同樣であり，且つ實驗物體もその形狀を圓壔形となした事は前回と同じである．砂の如き粒狀體の物體を圓壔形に作る場合には，砂が適度に濕つて居ればよいが，或程度以上に濕つて居る場合や全く乾燥して居る場合などに於ては砂を圓壔形にする事が出來ない．斯樣な場合にはセロフアン紙を用ひて圓壔を作りその中に砂を詰めて實驗を行つた．

實驗によつて得られた結果は土の場合と同じく，砂の彈性的性質は砂の種類，packing の狀態，含水量の如何によつて著しく支配される事である．而も含水量を徐々に増加すると含水率18〜20% 位迄は縱波も横波もその速度を減少するが，含水率20% 以上になると横波の速度は非常に小さなつて觀測されない程度となるに反し，縱波の速度は又再び大きくなる事が判明した．斯樣な狀態は多分液體の性質の表はれであると考へられる．又砂の彈性的性質は其の中に存在する粘着性のコロイド物質や，粒徑の極めて小さい物體によつて著しく影響を受ける．これは所謂 Thixotropy の樣な現象が表はれて居る爲ではないかと考へられる．又速度から普通の彈性式と同樣な式によつて砂の彈性係數を强いて求めると含水率10% 位迄は土と同じやうに 10^8 (c.g.s) 程度のものが得られた．

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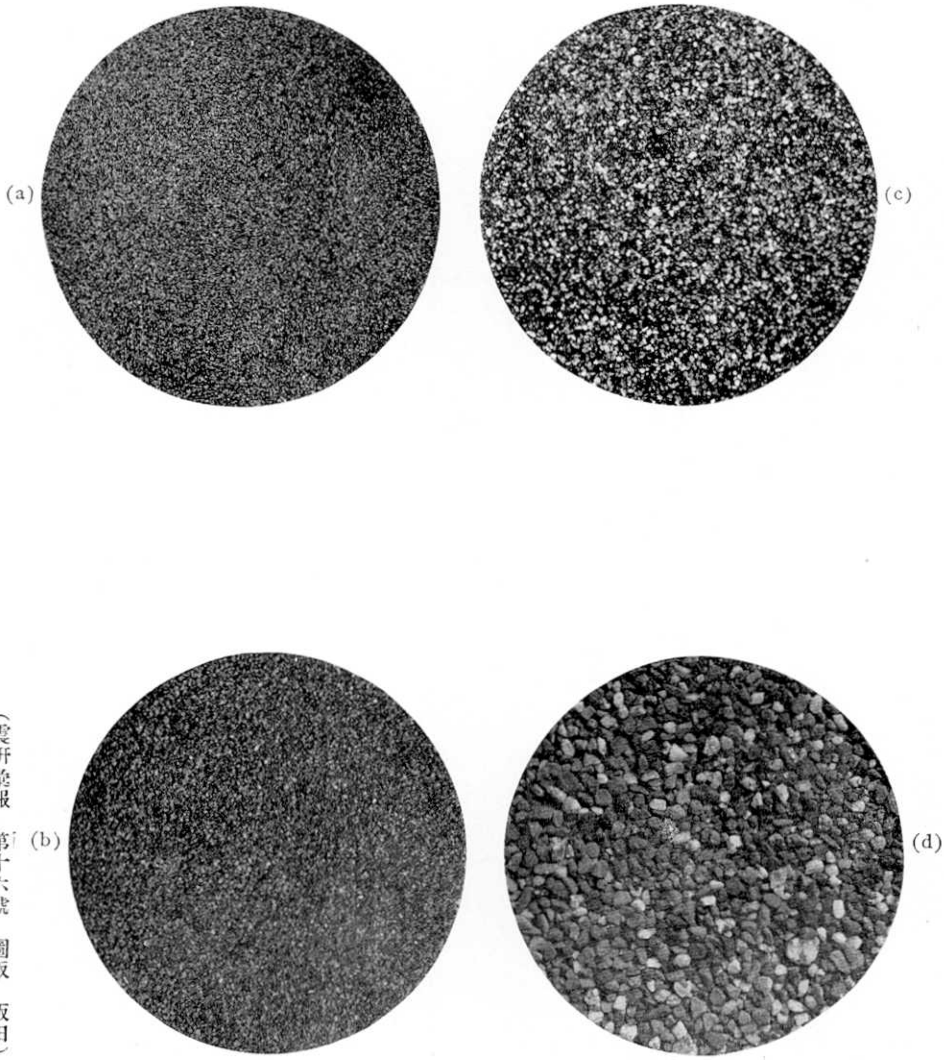

Fig. 1. Photographs showing the grain size of sand specimens.

(a) Sand No. 1 (actual size). (b) Sand No. 2 (actual size).
(c) Sand No. 3 (actual size). (d) Sand No. 4 (actual size × 1·3).