Remediation of contaminated musical sand
Amélioration du sable musical contaminé

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ABSTRACT: Musical-sand is an interesting coastal sand which makes a beautiful sound by shuffling one's feet. This musical-sand is very sensitive to environmental changes and instantaneously stops its sounds if mixed with just a little dust. It is an important view in this paper that it is really worth keeping musical-sands clean and in their original state. Therefore, this paper describes the distribution of particle sizes of musical-sand, the quartz particle content, the sound characteristics and practical applications of restoration to two contaminated musical-sand beaches.

RESUME: Il y a des sables côtiers dont on peut entendre la musique en les foulant. C'est ce qu'on appelle le sable musical. Ce sable est très sensible aux variations d'environnement, et s'arrête instantanément de bruire dès qu'il est un peu sale. Dans la "coexistence/symbiose entre l'architecture et "l'environnement", il est essentiel de sauvegarder le sable musical. La présente étude s'intéresse à la répartition des grains de sable musical, à sa teneur en particules de quartz et à ses caractéristiques musicales, et rapporte leur application au rétablissement réel des côtes de sable musical.

1 INTRODUCTION

There is an interesting beach sand where we can listen to a beautiful "Qui,Qui" by pulling our hand through it or shuffling our feet. This beach sand is what is known as musical-sand or barking sand, which contains a lot of bright quartz particles (Bolton & Julien 1883, Fairchild & Fippin 1920). Musical-sand is formed over a tremendously long period and has recently been recognized as an important natural heritage. Therefore, civil engineers have to pay deep attention to keeping it in a good condition while making progress with planning and construction. However, musical-sand beaches in Japan have been destroyed one by one and even those that have remained have lost their beautiful sounds. This paper proposes how to preserve this musical-sand in an excellent state and how to restore it to its original condition. The significant points of this paper are the following:

(i) The first half of the paper examines the properties of natural musical-sand such as the distribution of particle size, the quartz particle content and the relationship between the particle size and sound characteristics.
(ii) In the second half of the paper, the practical applications of two cases of the restoration of musical-sand beaches are introduced in this study.
(iii) Further, a technique to make it possible to produce the same artificial musical-sand as an actual musical-sand beach has been proposed in order to examine both the mechanism of sound-production and the remediation of contaminated musical-sand.

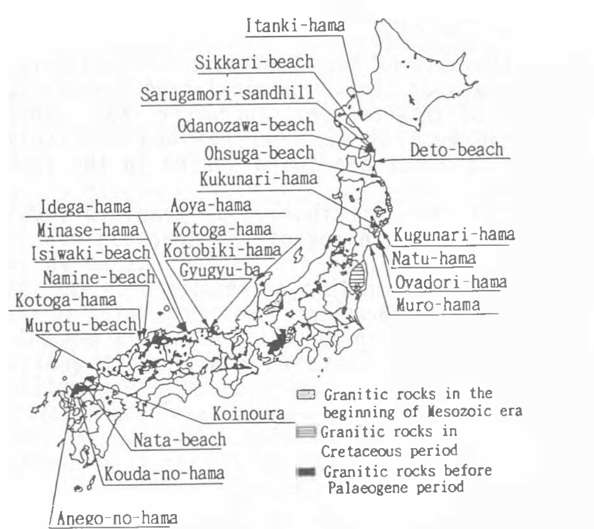

Fig. 1 Musical sand beaches and Granitic rocks

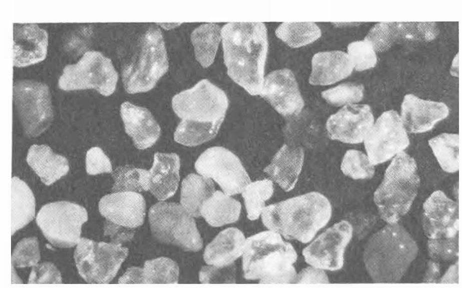

Photo.1 Musical-sand

2 MUSICAL-SAND BEACH

We investigated more than 90 beaches that were thought to contain musical-sand during a decade. It was discovered that good musical-sand beaches numbering 25 remained unchanged, mainly both in the west region of Japan facing the Sea of Japan and in the northern region of Japan facing side of Pacific Ocean, as shown in Fig.1. Further, with regard to over a hundred historical materials and

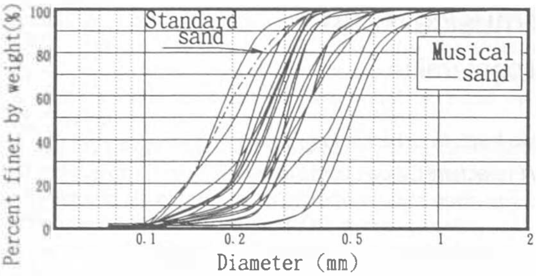

Fig. 2 Distributions of particle sizes

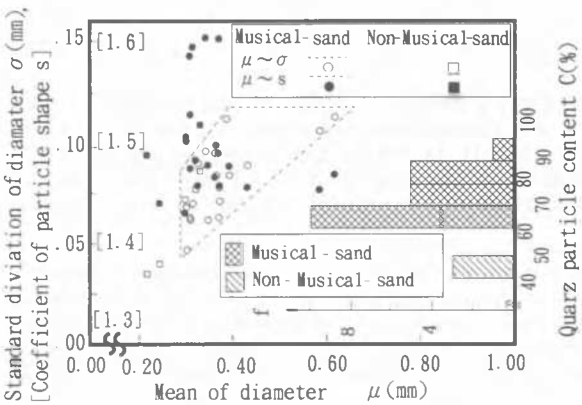

Fig. 3 Quartz particles

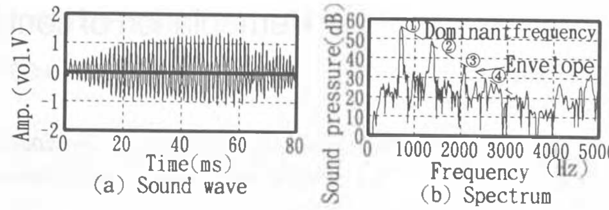

Fig. 4 Topical musical-sand

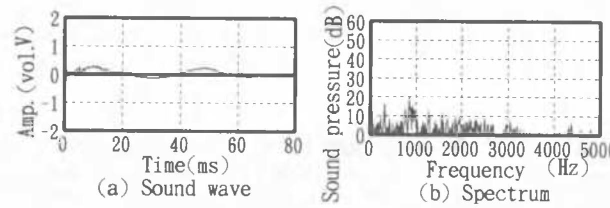

Fig. 5 Non-musical-sand

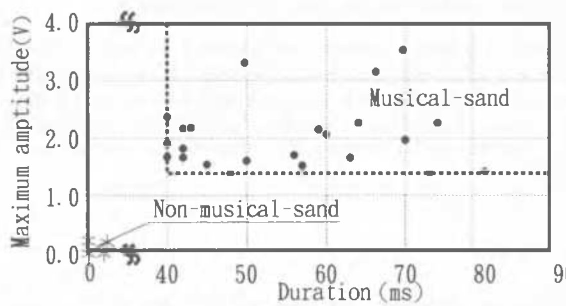

Fig. 6 Sounds of musical-sands

records, the authors have been able to confirm the existence of more than 60 musical-sand beaches in the middle of this century. Therefore, the number of Japanese musical-sand beaches has certainly decreased to about one-third during in the last fifty years.

Looking at the distribution of granitic rocks zones from the biginning of the Mesozoic era to just before the Palaeogene Period, as shown in Fig.1, it can be seen that a landside over what is now a musical-sand beach necessarily occured in the Granitic rock zone. As shown in Photo.1, a musical-sand consequently contains many bright quartz particles, the hardest mineral of the granitic rocks, because the quartz particles of the granitic rock remained due to weathering and erosion actions and were transported through rivers to a nearby seashore and formed a musical-sand beach.
These quartz particles greatly contribute to sound-production when they are rubbed against each other.

It is known that the topographical characteristic of Japanese musical-sand beaches can be made in the following two points. Most of musical-sand beaches, where the beach line L is less than 200m in length and the coefficient of beach shape (W/B), which denotes the length of plane depth of the bay W divided by the width of bay B, is in the range of 0.2 to 0.4, shown actually with a properly curved line.

Results mentioned above can indicate both the actual facts that musical-sand may be less likely to migrate away because sand movement is dominatly in a right angle to the beach line rather than in a parallel direction, and it can be kept in a good condition because the amplified sea waves in the bay wash it and refresh it.

3 PHYSICAL PROPERTIES OF MUSICAL-SAND

The density of musical-sand particles ρ_s is about 2.65g/cm^3. The maximum unit weight γ_{dmax} and the minimum unit weight γ_{dmin} is between 16.0kN/m^3 to 16.5kN/m^3 and 14.0kN/m^3 to 14.5kN/m^3, respectively. It can be shown that the minimum void ratio e_{min} and the maximum void ratio e_{max} is 0.6 to 0.65 and 0.8 to 0.9, in the maximum frequencies, all of which, however, are nearly similar to that of general sands. From the distribution of particle sizes through a sieves test as shown in Fig.2, the average particle size D_{50} is usually 0.3mm to 0.4mm, the same size as other Japanese beach sands and the uniformity coefficient U_c is able to be plotted in a range of 1.4 to 1.6, which is poorly particle grade. Thus, the foundamental properties of musical-sand have nothing special about them.

Next, we examined in detail the characters of quartz particles by using the Image Processing Method. The authors could observe, as seen in Fig.3, that the quartz particle size D of sand is shown by the mean value μ more than 0.3mm, and the standard diviation σ is less than 0.1mm, the quartz particle content C is more than 60% and that the coefficient of quartz particle sharp s is between 1.45 and 1.6. Where C denotes the number of quartz particle in the percentage of all particles, and s is equal to $(l^2\pi)/4A$, where in a perfectly round particle s=1.0 and l denotes the longest diameter of a quartz particle and A the section area, the larger the value of s is, the more squarish a sand particle is.

4 SOUND CHARACTERISTICS

4.1 *Sound-production*

As shown in Photo.2, original test equipment, in which a ceramic rob can penetrate, with constant air pressure at 0.1MPa, 150cm^3 of musical-sand in a bowl of the same material was manufactured in order to study sand sound-production. A sound wave, observed by the sound level meter, can be easily seen in a spectrum diagram with the FFT Analyzer. Figs.4 and 5 each have two figures that first indicate a topical sound wave along the time axis and then a transformed spectrum diagram of musical-sand and non-musical-sand, respectively. It can be enough be recognized from a musical-sand of Fig.4 that a sound wave along the time axis clearly has large amplitude effects (defined as the sound intensity) repeated for about a second. The spectrum diagram is composed of the first most dominant frequency (defined as the sound level) and then later a few less dominant frequencies to make it possible not only to arrange in the order of multiple numbers but also to keep the gradient line of the envelope (defined as the sound tone) straight to the right-down. The sound characteristics mentioned above are similar to those of musical string instruments, beautiful sounds such as those of a violin. While non-musical-sand can not make a reasonable musical sound but only noise, as shown in Fig.5.

4.2 *Characteristics of quartz particles and sounds*

Many interesting results, shown in both Figs.6 and 7, can be enough acquired from the detailed examination of various sounds of musical-sand. It can be understood in the figures that the sound characteristics are similutaneously satisfied with not only the zone enclosed by a dotted line of Fig.6, where the sound intensity is more than 1.4V in the maximum amplitude and the period of sound-production duration more than 40ms, but also the two dotted lines of Fig.7; in the first most dominant frequency is less than 1000Hz and the respondent sound pressure is more than 50dB and each gradient of the envelope of the later 2nd, 3rd and 4th less dominant frequencies is able to be plotted on an unique straight line. If beach sand is situated both of the dotted line zones of Figs.6 and 7, it is recognized as good musical-sand in view of sound characters.

The fact that the sound-production is strongly dependant on the distribution of the size of quartz particles is shown by the following:

Both Figs.8(a) and 8(b) show the relationship between the characteristics of quartz particles and musical sounds. It can be obviously indicated from figs.8(a) and 8(b) that the more the average size of the quartz particles and the quartz content is, the stronger the sound intensity is and the lower the sound level is. From the same approach, the authors have shown that the rounder the quartz particle is, the longer the period of sound-production duration is and the more echoing the sound tone is (Bagnold 1966, Criswell 1978).

In the simplest case, the quartz particles radially array themselves with other particles of equal diameter r into a hexagonal shape, as shown in Fig.9, and the sound characteristics will be theoretically enabled. Mechanical conditions of equilibrium in both the vertical and horizontal directions can be expressed by using the subscripts denoted in Fig.9 as follows:

$$\sigma_a \cdot r^2\sqrt{2}=N_{12}+T_{12} \qquad (1)$$

$$2\sigma_r \cdot r^2\sqrt{2}=N_{12}+N_2-T_{12} \qquad (2)$$

It can be shown in Eqs.(1) and (2) that the maximum ratio between the principal stresses (σ_a/σ_r), denoting the strength of this structural particulate materials according to the Mohr-Coulomb

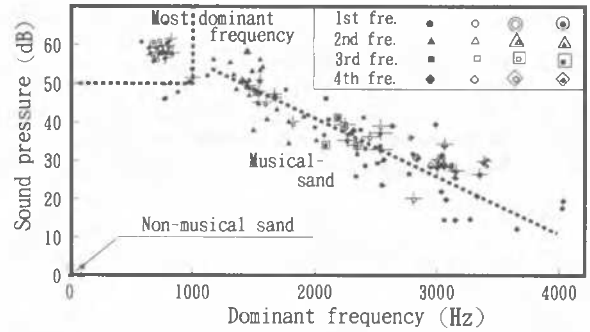

Fig. 7 Harmonic sounds

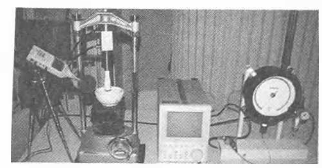
Photo.2 Sound test equipment

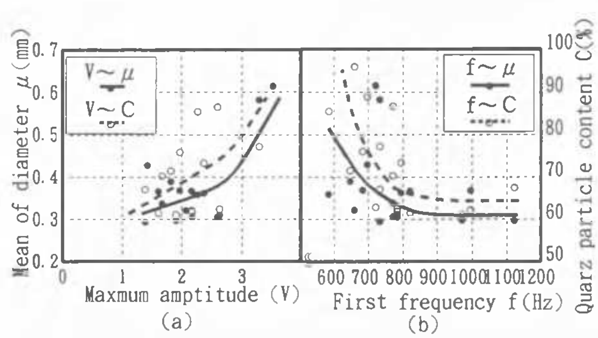

Fig. 8 Relations between quarz particles and sounds

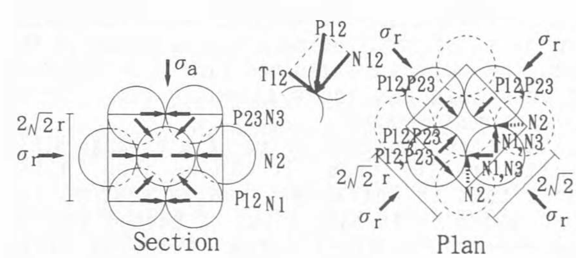

Fig. 9 Regular hexagonal

theory, is independent on the sphere diameter r. The tangential component T_{12} of the contact force P_{12} by which means the first layer acts on the second layer, can be given as follows:

$$T_{12}=\mu N_{12}=\tan\phi_\mu N_{12} \qquad (3)$$

where μ and ϕ_μ denote the coefficient and the angle of intergranular friction, respectively. By substituting Eq.(3) in either Eq.(1) or (2),

$$(T_{12}/T_{12}')=(r/r')^2 \qquad (4)$$

T_{12}' denotes the tangential component of contact force acting between equal-diameter spheres r' in the radius.

On the other hand, the average diameter d of the void of the sphere arrayed under the condition of the total volume ar^3 (a:constant) is easily obtained as follows:

$$\bar{d}=ar^3 n/b \quad (5)$$

where n and b denote the porosity in percentage and the number of voids, respectively. Based on Eq.(5), the relationship between the ratios of the average diameter of the voids and the particle sizes can be given as follows:

$$(\bar{d}/\bar{d}')=(r/r')^3 \quad (6)$$

and the number of the axial vibrations ν can be expressed as follows:

$$\nu=\{1/(c\cdot\bar{d})\}\sqrt{\gamma\cdot p/\rho} \quad (7)$$

where c denotes the constant under the condition of void edge, either opened or closed, and γ, ρ and p the specific heat, the unit weight and the pressure of the air or water in the void, respectively.

Accordingly, Eqs.(4), (6) and (7) show that the more a diameter size of sphere is, the more intensitive and the lower level the sound characteristics are and completely agree with the results of Figs.8(a) and 8(b).

5 REMEDIATION OF ACTURAL MUSICAL-SAND BEACHES

At Shirahama musical-sand beach on the Pacific Ocean side in Aomori Prefecture (designated as the Specific Preservation Seashore Area), along 2km in length, people enjoy swimming every summer. In spite of this, the beach sand could make a beautiful sound everywhere in the 1960's but we can never hear it now. Therefore, a plan to regain good sound was carried out there.

Investigated the material and physical properties of Shirahama sand, it can be understood that the sand has a lot of broken pieces of shell which obstructs restoration. As a result of first taking out a pieces of shell using a sieve 0.85mm in the stitch, the authors ascertained that this Shirahama sand is within the zones shown in Fig.3 to be defined as musical-sand.

Fig.10 shows two sound waves of a natural state and after restoration. It can be seen in the figures that in Shirahama sand, a restoration method, which is to wash 1.1kN of meshed sand by using a concrete mixer 35rpm with city water circulating at 10ℓ/min for a during of 10minutes, we are able to be clean it and reestablish good musical sound because a sound wave along the time axis as shown in Fig.10 can be plotted within or on the zones of Figs.6 and 7 recognized as the sound criteria of musical-sands. That is, it can be considered that Shirahama sand can completely regain its original state. At present, with reference to these good results, an actual field restoration has been established by the construction of a pilot plant.

On the other hand, a remarkable musical-sand beach at Sendai-hama in Ishikawa Prefecture, where the erosions due to storms and high water waves have sometimes forced a musical-sand to be removed offshore. This is where the plan that a concrete block for breakwater will be constructed offshore and the artificial musical-sand made of the quartz material is brought in is being carried out now. This artificial musical-sand produced by the authors has the same particle size as the actual Sendai-hama musical-sand and is able to make as beautiful a sound as the cleanest Sendai-hama sand, even under water, as shown in Fig.11. This success had been patented and has been applied to the mass production of musical-sand. It has been decided that Sendai-hama is to be enough reformed to where everybody can enjoy its musical sound and deeply consider it as the great natural heritage to be necessarily handed down in future.

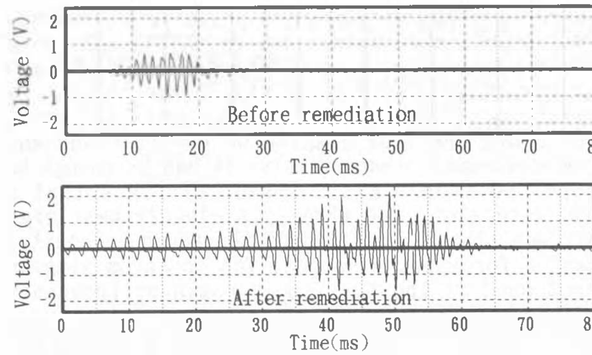

Fig. 10 Shirahama sand

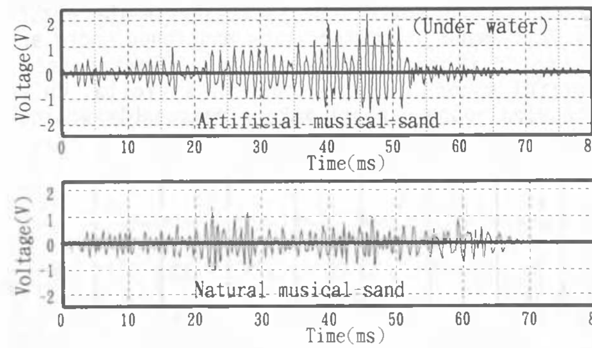

Fig. 11 Sounds of artificial musical-sands

6 CONCLUSIONS

This paper described valuable musical-sand in the practical views of how to keep it in good condition and to restore its original state. Conclusions obtained from this paper are summarized as follows;

(i) Japanese musical-sands can be expressed as a quartz particle having the average size of more than 0.3mm, the quartz content more than 60% and the larger the quartz particle is and the more the quartz content is, the more intensitive and the lower the sound is.

(ii) The practical applications of this study to restore of Japanese musical-sand beaches were introduced for the two cases.Especially notable that the success of using artificial musical-sand by the authors where it is not only the as same as an actual sand particle but also to make a good sound is very effective to remedy contaminated musical-sand-beach is possible.

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