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ORIGINAL PAPER

The Effect of Shape on the Linear Relationship of Maximum and Minimum Void Ratios of Various Sand Types

Seda Çellek

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Abstract Clean sands taken from the Trabzon, Sinop, Zonguldak and Çine regions of Turkey were used in this study. They were named, in order, Type 1, Type 5, Type 9, and Type 13. The samples were obtained by washing four sands through a no. 200 sieve. Type 1 is composed of 53% augite, and its specific gravity is 3.44. Type 5 is composed of 57% SiO_2, and its specific gravity is 2.74. Type 9 is composed of 80% SiO_2, and its specific gravity is 2.75. Type 13 is composed of 48% SiO_2, and its specific gravity is 2.75. Changes in mineral proportions were observed before and after washing of the sand. In this research, the procedures outlined in ASTM Standards D4254 and D4253 and the Kolbuszewski (in: Proceedings of the 2nd international conference in soil mechanics and foundation engineering, Rotterdam, vol 1, pp 158–165, 1948) method were used to determine maximum and minimum void ratios (e_{max} and e_{min}). In the study, the linear relationship between e_{max} and e_{min} was investigated, and an attempt was made to determine how much the grain shapes affected the linearity. For that purpose, the effects of e_{max} and e_{min} values on physical, mineralogical, and provenance location of the sand were examined, and various graphics were produced. R^2 values were calculated to examine the linearity of the distribution within each sand type. While Type 1 and Type 13 were close to each other in line, Type 5 and Type 9 gave values distant from linear.

Keywords Minimum void ratio · Maximum void ratio · Shape of grain · Sand · Sinop

1 Introduction

It has been clearly established that the values of maximum and minimum void ratios represent the loosest and densest conditions for sand. It has been demonstrated in the literature that e_{max} and e_{min} are key parameters for estimating the behavior of soil (Selig and Ladd 1973; Panayiotopoulos 1989; Cubrinovski and Ishihara 2002; Arasan et al. 2010; Chang et al. 2016). In the majority of the work on clean sand in the literature, the focus has been on those two parameters, such as the relationship between the material properties of e_{max} and e_{min} or void fractionation for sand classification (Selig and Ladd 1973; Miura et al. 1997; Shimobe and Moroto 1995; Cubrinovski and Ishihara 1999).

The values of maximum and minimum void space for sand are related to factors such as grain size, mean particle size, uniformity coefficient C_u, and excess void ratios. There are several studies in the literature that provide empirical relationships for maximum or

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S. Çellek (✉)
Department of Geology Engineering, Kırşehir Ahi Evran University, Kırşehir, Turkey
e-mail: sedacellek@ahievran.edu.tr

minimum void ratio as a function of grain size, C_u, and grain size for washed sand (Selig and Ladd 1973; Youd 1973; Santamarina and Cho 2004; Cho et al. 2006; Chang et al. 2016; MacRobert and Torres-Cruz 2016). Studies in the literature indicate that maximum and minimum void ratios are affected by grain size, diameter, and distribution characteristics. Increases in mean grain size (D_{50}) and C_u will increase e_{max} and e_{min}, and an increase in grain angularity will increase the void ratio. The proportion of fine grains has a significant effect on the void ratio and both void ratios will increase with cornering, but the maximum void ratio shows a larger increase when compared to the minimum (Arasan et al. 2010). Thevanayagam et al. (2002) determined that the maximum and minimum gap ratios decreased with increasing roundness of the grains. The spacing range may vary widely, depending upon the grain size distribution and the packaging or array properties of the densities (Türköz 2014).

The maximum and minimum void ratios were experimentally determined according to established procedures. Various standard and nonstandard techniques have been proposed in the literature to achieve e_{max} and e_{min} values (ASTM D4253–00 2002; ASTM D4254–00 2002; Japanese Geotechnical Society 2000; Kolbuszewski 1948; Mulilis et al. 1977; Vaid and Negussey 1988; Chang et al. 2016). In research methods, variations are proposed on the basis of constraints determined by existing materials and equipment. Because repeatability is the key parameter for e_{max} and e_{min}, grain size, particle shape, and mineralogy are given for the proposed methods (MacRobert and Torres-Cruz 2016). For example, a compression method using a vibrating circular plate can be used as a standard laboratory test to estimate the cost of the test, but the resources required to conduct those tests are not always available (Riquelme and Dorador 2018). International ASTM Standard D4254 and the Japanese Geotechnical Society (JGS) have established standards for determining the minimum and maximum void ratios of cohesionless soils containing up to 15% and 5% fines, respectively. The use of saturated specimens for e_{min} detection has been proposed by Bolton (1986) (ASTM Standard D4253—Soil Maximum Index Intensity and Unit Height Using Vibration Table). None of the existing standard methods, such as ASTM Standard D4254—Minimum Index Density and Soil Density and Calculation of Relative Intensity or JGS, provide a procedure for determining the e_{max} value of sand deposited by water or slurry. Evaluation of e_{max} and e_{min} in coarse granular soils can be estimated by using the parallel transition method with minimum and maximum density tests, but there are many situations in which that alternative cannot be implemented, such as if the soil contains more than 10% by weight of fine material and/or if there is a high C_u transition. That is because, if those passes are scaled by parallel transition curves, the scaled samples will usually have fine particles in an amount greater than 10%. That means that the pass-through parallel method cannot be implemented (De la Hoz 2007). According to Carraro and Prezzi (2008), the maximum void fraction of natural soil deposits, such as those of alluvial and submarine soils, hydraulic deposits, and waste dams, cannot be judged appropriately by existing standard techniques. The reason is that all standard techniques available for e_{max} determination suggest using dried samples in an oven. In this study, e_{max} and e_{min} values of sand were determined by using ASTM Standard D4253 and the ASTM and Kolbuszewski (1948) methods. The determined values were plotted with the graphs used in the literature (Veiga Pinto 1979; De Almeida Maia 2001; De la Hoz 2007; Dorador and Besio 2013).

2 Literature Review

The maximum and minimum void rates for clean sands depend on several factors. They are parameters such as grain size, grain size, and C_u, and mathematical models are available in the literature (Selig and Ladd 1973; Youd 1973; Santamarina and Cho 2004; Cho et al. 2006; Chang et al. 2016). It is known that the e_{max} and e_{min} limiter void ratios are also affected by the method used to determine those parameters (Kolbuszewski 1948; Townsend 1973; Vaid and Negussey 1984; Youd 1973; Carraro and Prezzi 2008). Previous studies have attempted to establish a correlation between the maximum spacing index, e_{max}, and the e_{min} spacing index. Some authors have suggested a linear correlation between the two parameters (Veiga Pinto 1979; Cubrinovski and Ishihara 2002; Mayne et al. 2001; Dorador and Besio 2013; Riquelme and Dorador 2018). De la Hoz (2007) proposed a detailed methodology for evaluating e_{min} and e_{max} for coarse soils with C_u grades of 10% or higher. Chang et al. (2016) determined maximum and minimum void ratios for sand–clay mixtures. In that study, researchers prepared mathematical models by conducting experiments with 24 sand samples. They found a linear relationship between maximum and minimum voids for sand–silt mixtures. In addition, other studies show that third-order polynomial equations are reasonable to estimate the variation of minimum and maximum void ratios for fine-grained sand blends. Furthermore, different studies show that third-order polynomial equations are necessary to estimate the variation of the minimum and maximum ratio rates for minimum-grained sand blends (Yilmaz 2009). Othman and Marto (2018), in their study presents the effect of various range of fines content on minimum void ratio e_{min} and maximum void ratio e_{max} of sand matrix soils. They made some laboratory tests to determine e_{min} and e_{max} of sand matrix soil were conducted using non-standard method introduced by previous researcher. In the study by Miura et al. (1997), 200 specimens of the Toyoura Sand were catalogued by their physical properties, as well as by their maximum and minimum void ratios. The effects of fine grains on e_{max} or e_{min} in sands have been investigated to examine the effect of fine grains on the intact behavior of sand (Thevanayagam et al. 2002). Goudarzy et al. (2016) investigated the effect of fine grain content on the maximum shear strength. For that purpose, they calculated the maximum and minimum void ratios of the sand. Cubrinovski and Ishihara (2002) tried to characterize the maximum and minimum voids of sand, using 300 natural sand samples in their work. They investigated the effect of the maximum and minimum void fraction of sand on the characterization of the material. Cubrinovski and Ishihara (1999) made a general presentation to demonstrate the material properties of sand and used it for that purpose by preparing sand samples at different void compositions between tight and loose. Thus, approximately 150 minimum and maximum density tests were conducted, with most of them compiled from the relevant literature in accordance with ASTM D4253-00 and ASTM D4254-00 (indexes, magazines and geotechnical engineering conferences; Carraro and Prezzi 2008). To establish correlations between the maximum and minimum density tests in gravel and sand materials, geotechnical engineering studies were carried out to collect the data on the maximum density, minimum density, e_{max}, e_{min}, specific weight, and particle size distributions of solid particles (G_s). All information allowed to create a database classified by material type is based on maximum particle size (D_{max}), material origin, C_u, and particle shape (tangency) tests. The vast majority of those tests were performed according to ASTM Standards D4253 and D4254, but the database was completed with large scale density tests that used vibrating hammers in large steel molds. All the data were organized to produce a database, which was rated by kind of material, maximum particle size (D_{max}), material origin, C_u, and particle shape (angularity). The capacious generality of these tests were executed according to ASTM Standards D4253 and D4254, but the database was also complemented with maximum and minimum density tests performed on a grand scale by using pulsatory hammers in large steel molds (Marsal and Resendiz 1975; Contreras 1980; Dorador and Besio 2013).

3 Void Ratios and Textures of Sandy Soils

In geotechnics, the void ratio (e) is one of the most important parameters for expressing the engineering behavior of soils (Monkul 2005). The void ratio (e) is one of the important and fundamental parameters governing the geotechnical behavior of a parcel of land. Significant differences are observed in the properties of soil resistance or compressibility in soils with the same void ratio. One of the reasons for such different behaviors is the difference in the regulation of the soil particles, even if they have the same void space. This particle arrangement is sometimes referred to as the "ground structure", which is the most controversial subject in geotechnical engineering (Yükselen 2007). The term "bulk of voids" in the definition of void ratio refer to the area not occupied by mineral grains, and the void ratio is calculated from the known weight and volume (Terzaghi et al. 1996; Monkul 2005). The void ratio of typical granular soils is varied. Relative tightness, D_r, or density index, is used to compare a floor void ratio (e) to its minimum and maximum void ratios (Holtz and Kovacs 2002). When a sandy soil or a finely granulated mixture is examined more closely, the void volume can be divided into two subcategories—voids depending on the skeletal particles and voids depending on the finer particles (Fiès 1992; Mitchell 1993; Fiès and Bruand

1998; Thevanayagam et al. 2002; Abichou et al. 2002; Monkul and Ozden 2004; Monkul 2005).

Ground void ratio (e) is defined as the ratio of the void volume (V_v) to the solid volume (V_s) and is calculated by the following equation:

$$e = \frac{V_V}{V_S} \tag{1}$$

where e, void ratio; V_v, void volume and V_s, solid volume.

The largest gap rate that can be on a floor, or the loosest case, is called the maximum void ratio (e_{max}). Any flicker is obtained by pouring the dry clay into a mold in a specific and calibrated mold in the laboratory without permission. The e_{max} value can be calculated from the weight of the sand in a mold. Similarly, the minimum void ratio (e_{min}) is the most intensely compacted condition that a floor can have. To calculate the minimum void ratio, the specific dry bulk volume can be subjected to vibration in a known vessel (Holtz and Kovacs 2002; Türköz 2014). Relative density is an important parameter, but it is rarely evaluated on coarse granular soils due to difficulties in testing the maximum and minimum void indexes (e_{max} and e_{min}). Geotechnical characterization of coarse-grained materials, such as quarrying materials and waste rocks produced by mining processes, has always been challenging due to the presence of extreme-sized material that represents a problem for sampling and laboratory testing (Riquelme and Dorador 2018). The result is that, at the same intergranular spacing (less than the maximum spacing of the main sand), the slip resistances are not similar for the silty sand and the main sand (Monkul 2005).

In sand, the void ratio is usually between 0.5 and 0.9. It is predicted that the void ratio in sand would be not less than 0.3 or more than 1.2. Typical minimum and maximum void ratio values for various ground types (Genç 2011; Çellek 2016) are given in Table 1.

Table 1 Typical void ratio values (Genç 2011; Çellek 2016)

Ground types	e_{max}	e_{min}
Equivalent spherical ground (theoretical value)	0.35	0.91
Clean, fine-medium grained sand	0.40	1.00
Uniform inorganic silt	0.40	1.10
Silty sand	0.30	0.90
Mica bearing sand	0.40	1.20
Silty sand and gravel	0.14	0.85

4 Materials and Methods

4.1 Field Studies

Various granular materials were used in this study to investigate the physical properties of sands with regard to the influence of primary characteristics. Four sand samples were prepared and classified into beach sand and alluvial sand. Ten kilograms of sand was taken from the locations chosen as the study area. In the study, the sand samples used were taken from the coastal areas of Trabzon (Type 1), Sinop (Type 5), Zonguldak (Type 9), and from the Menderes River (Basin) of Çine (Aydın) (Type 13) (Fig. 1).

Samples with different primary properties were selected from sands that were collected from rivers and beach areas and were derived from areas bordered by volcanic, sedimentary, and metamorphic rock units (Fig. 2).

4.2 Mineralogy of Sands

The mineralogical contents of the sands have been determined by XRD studies, together with an illuminated microscope and an optical microscope. Grain shapes of the sands were determined by SEM images (Fig. 3).

The most angular grains belong to the Type 1 sand, in which the augite minerals are most commonly detected. Type 1 and Type 9 sand are marine in origin, whereas Type 5 samples were of marine and alluvial origin. Type 13 sand was taken from the side of a river. Type 9 sand contains relatively rounded granules. In Type 5 sand, semi-angular and semi-round granules are observed. Type 13 sand contains semi-angular grains similar to those of Type 1 sand (Table 2).

4.3 Experiments

Grains with diameters larger than 2.00 mm or smaller than 0.075 mm in nominal diameter were removed by sieving and washing with water, but the natural grain size distributions were basically retained. The sands used were taken from four different part of Turkey; they did not have ASTM Standard numbers and are

Fig. 1 Locations of the samples taken for the study

unknown in the literature. Figure 3 shows the grain size distribution of the sands, which are classified as *SP* according to the USCS. SP groups are poorly sanded soils which containing zero or very small amounts of non-plastic material (Fig. 4).

Vertical particle size distribution curves reflect small particle size. These are known as poorly graded soils or uniformly graded soils. The condition of grading a sand-shaped soil is determined by graphically drawing the grain size distribution of that soil and calculating the curvature coefficient C_c with uniformity coefficient C_u on this curve. Particle diameters corresponding to specific percentages for a given soil are known as D dimensions. D60 is the grain diameter corresponding to 60% by weight or by mass. For example, D10 is the grain size corresponding to 10%. So 10% of the soil is thinner than D10. D10 is called the effective diameter and D50 is called the average diameter (Çellek 2016; Kayabalı 2010; Mahmutoğlu and Kayabalı 2006; Aytekin 2004). Two additional parameters, uniformity coefficient (C_u) and curvature coefficient (C_c) are based on dimensions D:

$$C_u = \frac{D_{60}}{D_{10}} \tag{2}$$

$$C_c = \frac{(D_{30})^2}{D_{10}D_{60}} \tag{3}$$

C_u, uniformity coefficient; C_c, curvature coefficient.

Sand particle diameters ranged from 0.07 to 2 mm. The coefficients of uniformity, C_u, C_c, D_{10}, D_{30}, and D_{60}, and the mean grain size, D_{50}, of the sands are given in Table 3.

While the C_u values of the steep curves reflecting poorly graded soils are low, the curved curves (well graded floors) have high values. The values of the flat curved soils are between 1 and 3; irregular curves have higher or lower values (Çellek 2016; Kayabalı 2010; Mahmutoğlu and Kayabalı 2006; Aytekin 2004).

The relative density of the field void ratio, e between maximum void ratio, e_{max} and minimum void ratio, e_{min} (Lade et al. 1998) can be defined as:

$$D_r = \frac{e_{\max} - e}{e_{\max} - e_{\min}} \times 100 \tag{4}$$

D_r, relative density; e_{max}, void ratio of coarse grained soil (cohesionless) in its loosest state; e_{min}, void ratio of coarse grained soil (cohesionless) in its densest state; e, void ratio of coarse grained soil (cohesionless) in its natural existing state in the field.

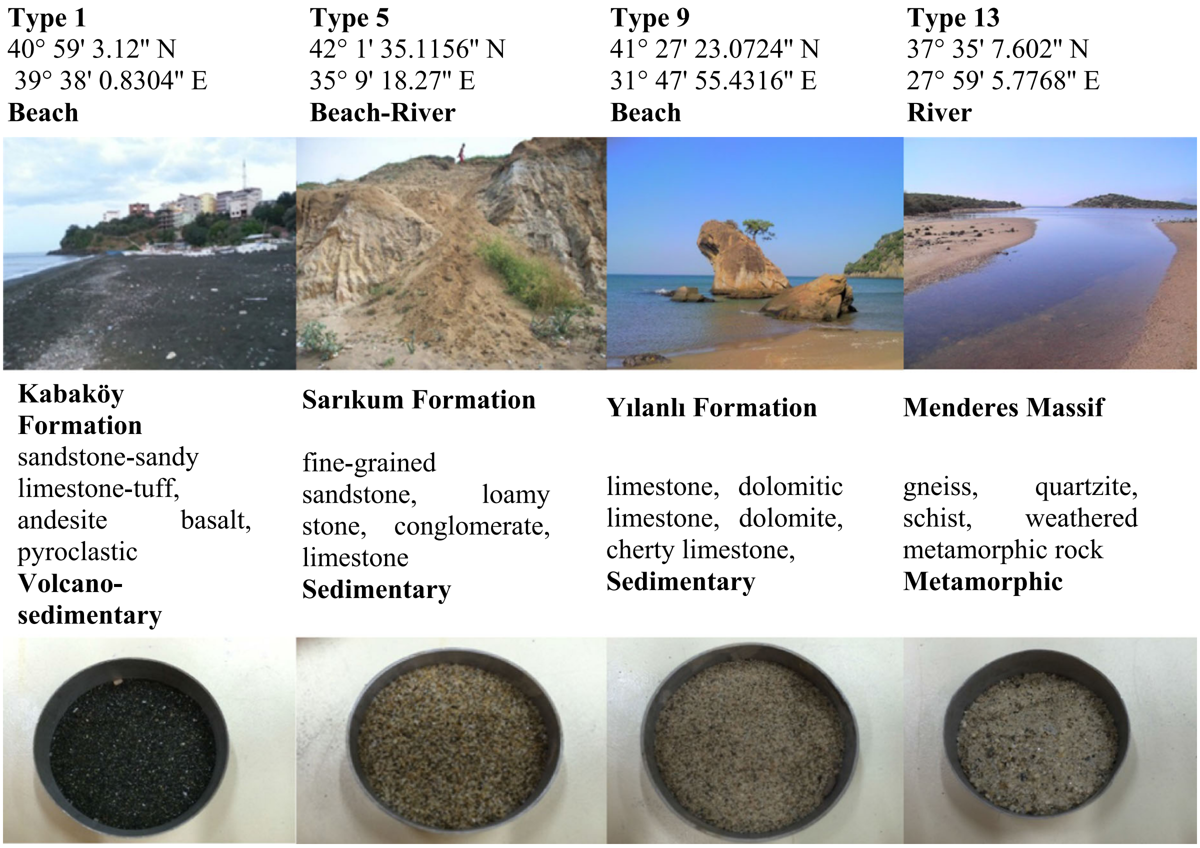


Fig. 2 Sand samples used in experiments and field photos of the place that samples were collected

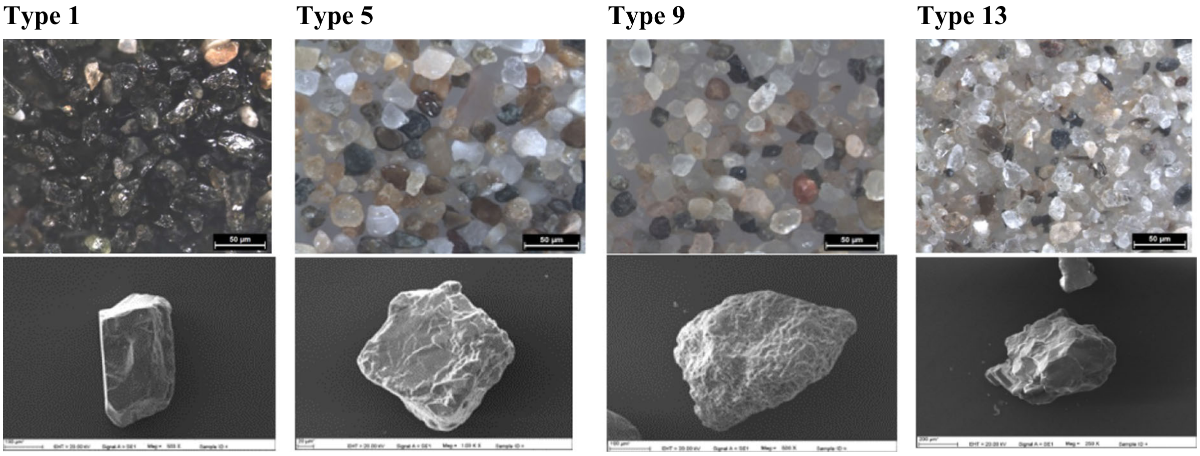


Fig. 3 Optical microscope and SEM images of the sand samples

The diagram of theoretical variation of minimum and maximum void ratio in binary packing is shown in Fig. 5 (Othman and Marto 2018).

Maximum and minimum densities of sand samples were measured in the experiments. Maximum ($e_{\max par}$) and minimum spacing ($e_{\min par}$) were calculated by means of the empirical formulas (Table 4).

Table 2 Mineral contents of the sand samples (Çellek 2016)

Sand	wt%	Name of the mineral	Mineral formula
Type 1	53	Augite	$Ca(Mg, Fe)Si_2O_6$
	20	Diopside	$Ca(Mg, Al)(Si, Al)_2O_6$
	20	Hedenbergite	$CaFe^{+2}\ Si_2O_6$
	7	Fayalite	$Fe^{+2}\ SiO_4$
Type 5	57	Quartz	SiO_2
	43	Anorthite	$CaAl_2Si_2O_8$
Type 9	80	Quartz	SiO_2
	20	Anorthite	$CaAl_2Si_2O_8$
Type 13	48	Quartz	SiO_2
	31	Anorthite	$CaAl_2Si_2O_8$
	20	Muscovite	$KAl_2Si_3AlO_{10}(OH)_2$

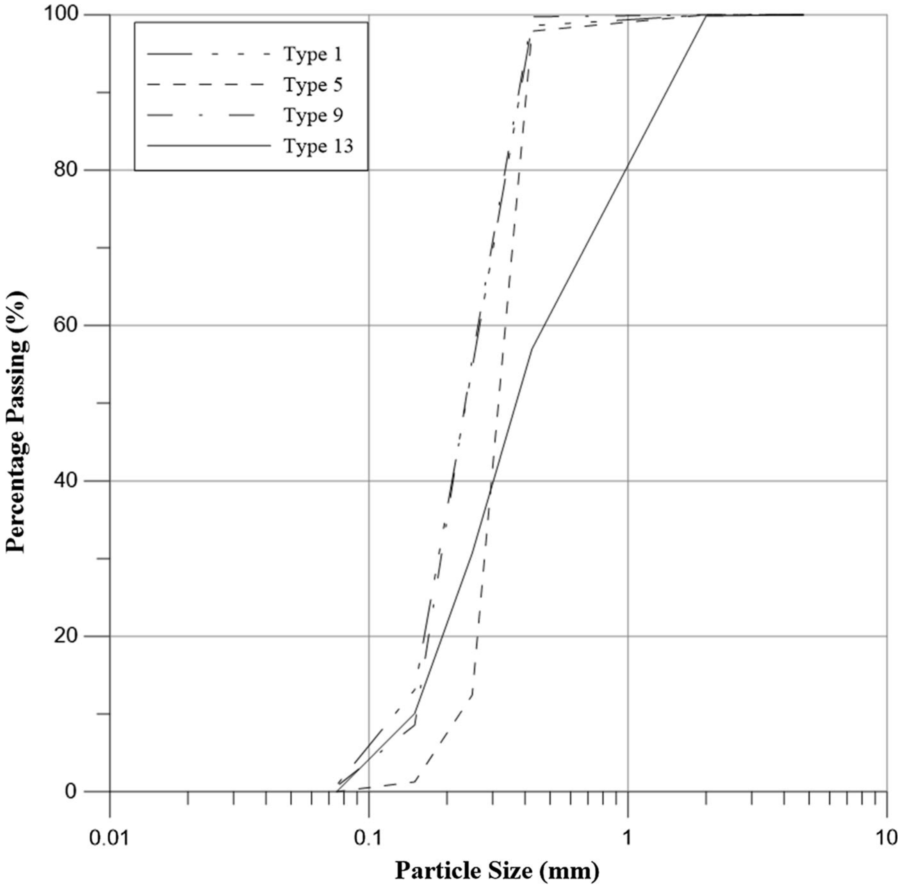


Fig. 4 Grain dispersion curves of sand samples

The averages of the obtained values were taken, and the calculated values are as follows: Types 1, 5, 9, and 13 minimum mean void ratios are 0.669, 0.584, 0.615, and 0.612, and the maximum mean void ratios are 0.905, 0.793, 0.834, and 0.925, respectively.

Specific Gravity (Gs) is the ratio of specific gravity of the solid to the specific gravity of water. It can obtained by measuring the weight of solid to the weight of water occupying equivalent volume of water. In other words, determination of porosity using a water pycnometer with capacitive level detection,

Table 3 Index properties of the sands used in this study

	Type 1	Type 5	Type 9	Type 13
C_u	2.123	1.502	1.728	3.178
C_c	1.016	1.035	0.893	0.852
D_{10}	0.126	0.224	0.152	0.149
D_{30}	0.185	0.279	0.189	0.246
D_{50}	0.236	0.316	0.235	0.369
D_{60}	0.267	0.336	0.263	0.474

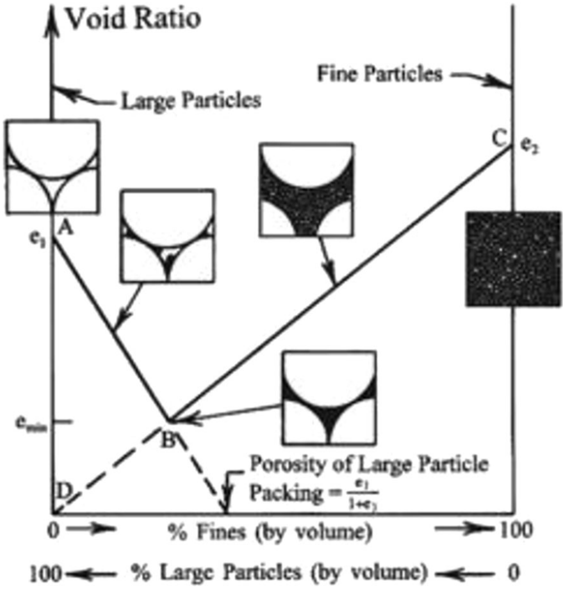


Fig. 5 Theoretical variation of void ratio with fines in binary packing (Lade et al. 1998) quoted by Othman and Marto (2018)

$$M_{water\ displaced\ by\ soil} = \rho_{water} \times V_s \tag{5}$$

where $\rho_{water} = density\ of\ water\ at\ temperature\ tested$

$$\text{So } M_{pws} = M_s + M_{pw} - \rho_{water} \times V_s \tag{6}$$

$$\text{Therefore, } V_s = \frac{M_s + M_{pw} - M_{pws}}{V_s} \tag{7}$$

Combining with equation set

$$Gs\left(\frac{M_s}{M_s + M_{pw} - M_{pws}}\right)\left(\frac{\rho_{water}}{\rho_{water(20)}}\right) \tag{8}$$

M_{pw}, mass of the pycnometer full of water; M_{pws}, mass of the pycnometer full of water with soil; M_s, dry mas of soil.

Specific gravities of Type 1, Type 5, Type 9, and Type 13 used in the study were determined to be 3.44, 2.74, 2.75 and 2.75, respectively, according to ASTM Standard D854.

The graph below was drawn to show the relationship between the maximum and minimum void ratios of the sands. While Types 1, 5, and 9 are distributed on a line, Type 1 has a different range distribution. In addition, R^2 values were calculated to examine the linearity of the distribution within each sand type. While Type 1 and Type 13 were close to each other in line, Type 5 and Type 9 gave values distant from linear. The mean values of e_{max} and e_{min} were added to the graph to show the linearity between the sands more clearly (Fig. 6).

Although the Type 5 sand is marine and contains a small alluvial addition, it is evaluated together with

Table 4 e_{max} and e_{min} values of sand samples

Type 1			Type 5			Type 9			Type 13		
e_{max}	e_{min}	$e_{min} - e_{max}$	e_{max}	e_{min}	$e_{min} - e_{max}$	e_{max}	e_{min}	$e_{min} - e_{max}$	e_{max}	e_{max}	$e_{min} - e_{max}$
0.898	0.660	0.238	0.760	0.550	0.210	0.818	0.596	0.222	0.921	0.596	0.325
0.906	0.670	0.236	0.778	0.564	0.214	0.827	0.609	0.218	0.921	0.603	0.318
0.910	0.676	0.234	0.786	0.587	0.199	0.829	0.612	0.217	0.924	0.604	0.321
			0.788	0.605	0.183	0.849	0.613	0.237	0.927	0.607	0.320
			0.851	0.615	0.235	0.850	0.649	0.201	0.931	0.649	0.282
0.910	0.660	0.250	0.851	0.550	0.300	0.850	0.596	0.254	0.931	0.596	0.335

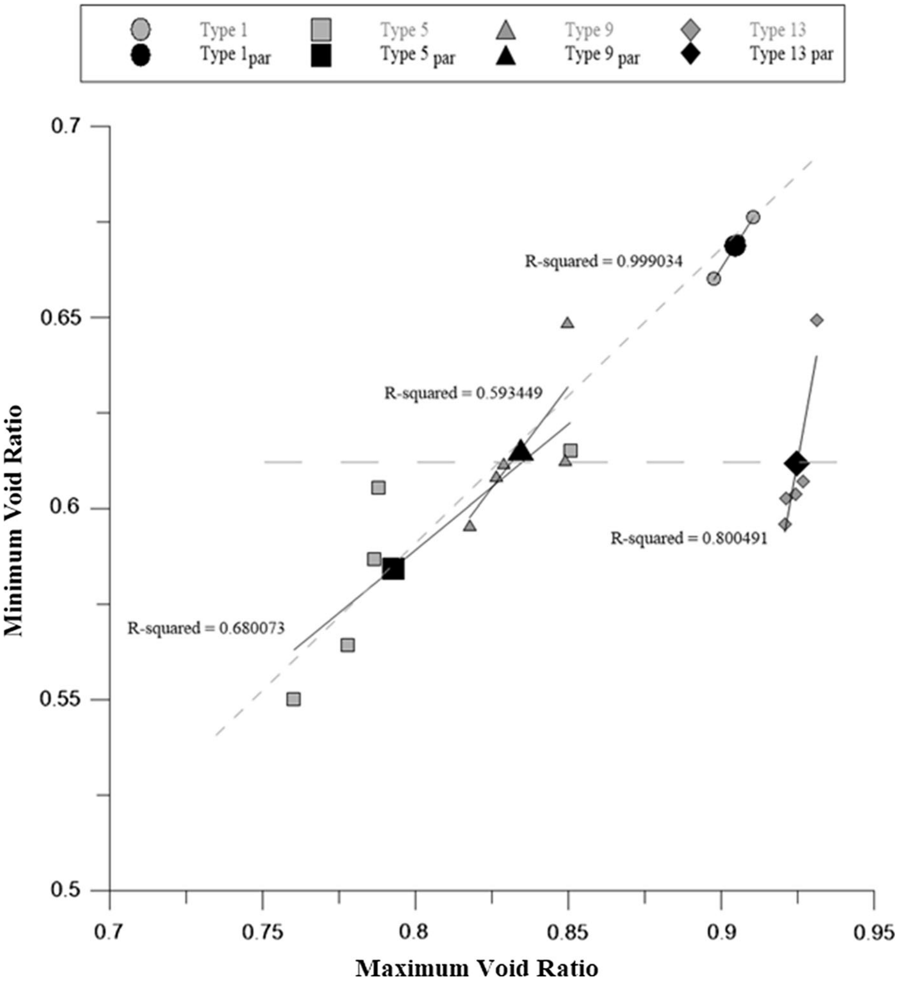


Fig. 6 Relationship between e_{min} and e_{max} (Veiga Pinto 1979; De Almeida Maia 2001; De la Hoz 2007)

Type 1 and Type 9 sands, and the linear relationship between marine sand and R^2 values was determined to be 0.903 (Fig. 7).

Figures 7b, 8 and 9a were drawn to aid in understanding the relationships between e_{max}, e_{min}, mean grain size (D_{50}), and the uniformity coefficient (C_u).

It is seen that the values of the maximum void ratios of three sand samples (with the exception of Type 5 sand with $D_{50} = 0.316$) increase with the D_{50} value. C_u values increase with both e_{max} and e_{min} values.

When the variation of C_u values relative to the average e_{max} and e_{min} values are examined, it is seen that C_u increases with the maximum void ratio value but that this linear relationship shows a difference in the minimum gap. River sand (Type 13) shows a difference when the C_u value of sea sand is increasing. According to the grain distribution curve, it is seen that Type 1 and Type 9 sands are almost coincident and that Type 5 sand is close to them. It is seen that the maximum and minimum void ratios of sand differ according to D_{50}.

5 Discussion and Conclusions

Numerous studies have been published in the literature regarding maximum and minimum void ratios. Those studies have addressed mineralogy, fracture, grain size, diameter, and distribution characteristics of maximum and minimum voids. In this study, unlike the others, the variation of the linear relationship between e_{max} and e_{min} values was studied by means of grain shape.

Types 1, 5, and 9 sand samples were taken from the seashore, and Type 13 sand was taken from the edge of a river. Type 5 sand has both marine and alluvial

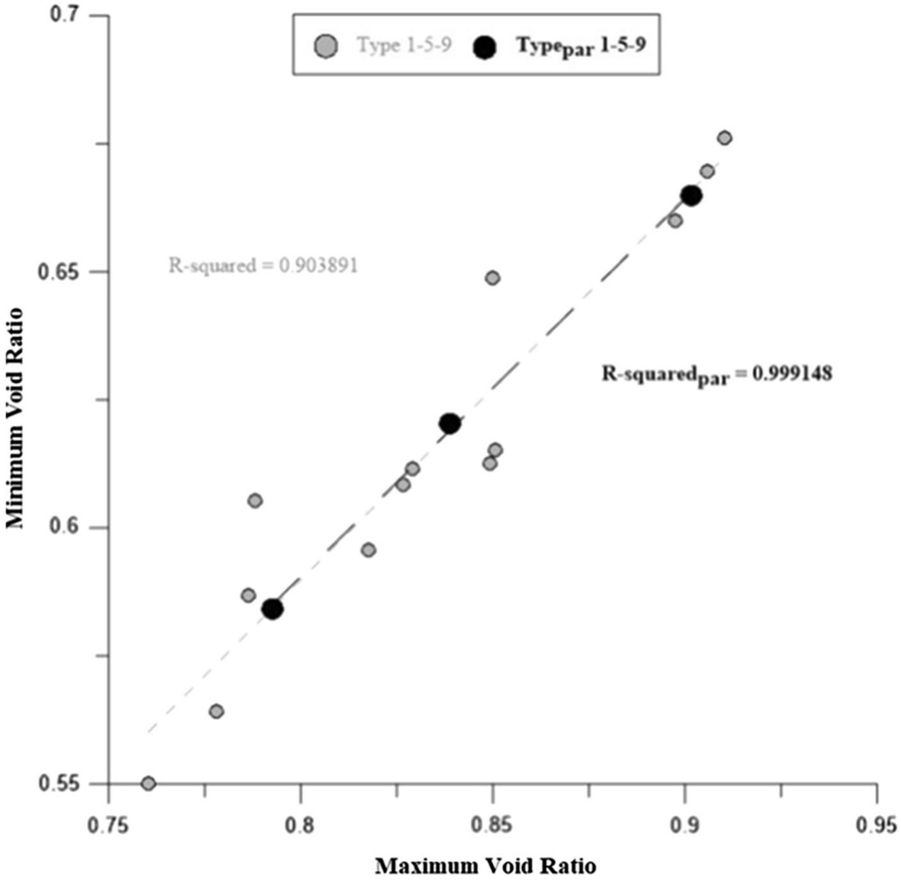


Fig. 7 Relationship between e_{min} and e_{max} for marine sands

origins (Aktimur 1993). Type 1 sand is mineralogically different from the other three types. It was determined that the Type 1 sands are originated from basaltic rock, which is more durable than the other three types. It is expected that sea sand will contain more rounded grains than the alluvial sands, but with the effect of mineralogy, the most angular grains were found in the Type 1 sand. Semi-round grains were found in Type 9 sand. Type 13 sand is similar to Type 9 sand, but it also contains particles similar to those in Type 13 sand.

Type 5 ($R^2 = 0.999$) and Type 13 ($R^2 = 0.800$), with sand-like maximum–minimum void ratios, gave similar values that were nearly linear. Type 5 (0.680) and Type 9 (0.593) were deviated linearly. That shows that, under normal conditions, the linearity between the maximum and minimum gap ratios of sea sand made of SiO_2 is impaired. The reason may be that the granules have a more rounded structure.

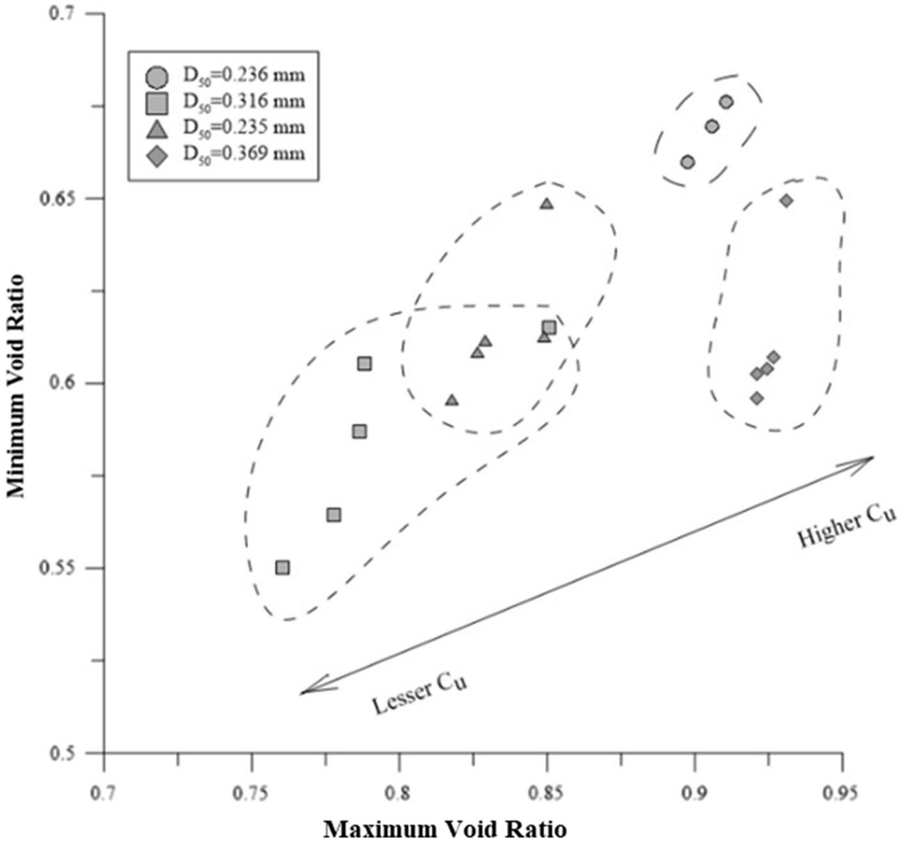
The specific gravity of the sands has standard values, except for that of Type 1. Due to its mineralogical content, Type 1 has a specific gravity value of 3.44, whereas the other sands, intensely composed of SiO_2, have specific gravity values between 2.74 and 2.75.

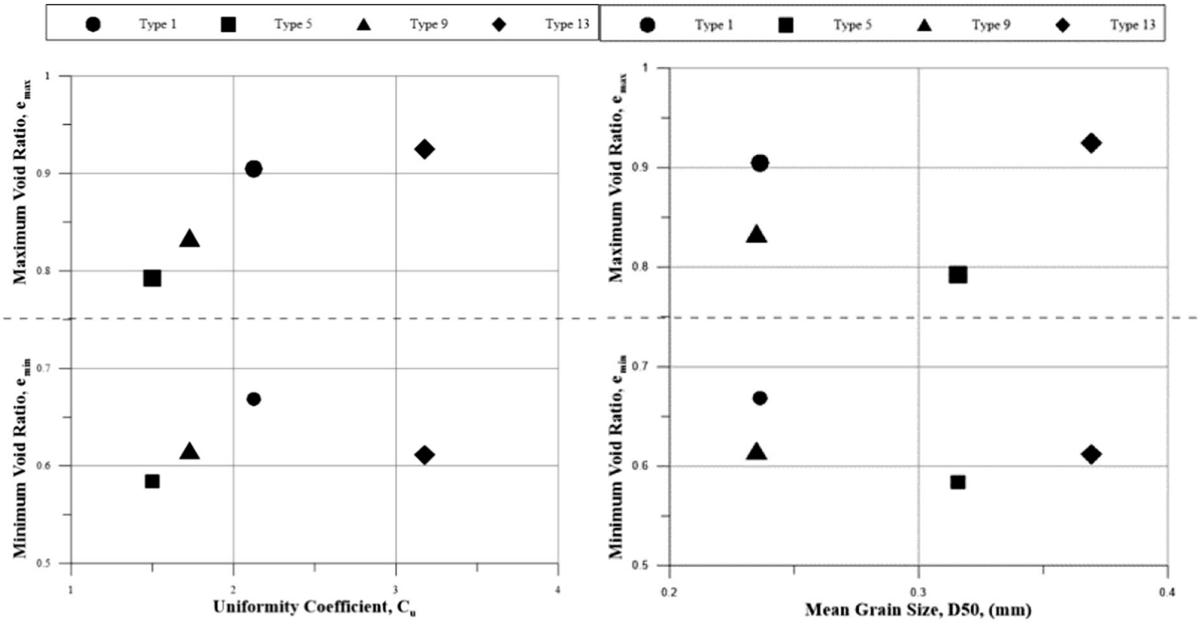
Type-1 (R2 = 0.999) and Type 13 (R2 = 0.800) sand-like maximum–minimum void ratios give similar values to linear Type 5; (0.680) and Type 9 (0.593) were deviated linearly. This shows that under normal conditions, the linearity between the maximum and minimum gap ratios of sea-sand made of SiO_2 is impaired. The reason for this may be that the granules have a more rounded structure.

On the other hand, as the angular grain proportion increases in the material, we can also mention the existence of a linear relationship between e_{max} and e_{min}. In the case of the marine sand, the linear relationship between the reverted mean values is 0.999.

It is seen that the e_{max} values of the other three sand types, except for Type 9, increase with D_{50} values. That is because the other three sand types are derived

Fig. 8 Relationships of e_{min} and e_{max} values of sand with D_{50} and C_u (Dorador and Besio 2013)





(a) (b)

Fig. 9 **a** Relationship of e_{max} and e_{min} values of sand to uniformity coefficient (C_u), **b** relationship of e_{max} and e_{min} values of sand to mean grain size (D_{50})

from single basins, whereas Type 5 sand has originated from two different source areas.

The sand shows an increasing relationship of void space with the C_u value. That increase is clearly seen between the maximum void ratio and C_u. That relationship has been disrupted by Type 13 sands for the minimum void ratio. That is because the Type 13 sand is connected to the river, and the other three types of sand are taken from the seashore.

The results of the study showed that the slope of the increase in angularity of the beads and the maximum–minimum void ratios approached linearity with the increase of roundness.

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