Acta Montanistica Slovaca
ISSN 1335-1788
actamont.tuke.sk

New Criterion for Shutter Designing by Dry Pluviation Method

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How to cite this article:
Cheshomi, A., Sadeghi, A. and Gholamhossein Zadeh, N. (2025). New Criterion for Shutter Designing by Dry Pluviation Method. *Acta Montanistica Slovaca,* Volume 30 (2), 458-469

DOI:
https://doi.org/10.46544/AMS.v30i2.15

Abstract
Dry pluviation is a technique applied to prepare sandy soil samples for physical modeling. In this method, soil particles rainfall in the mold after passing through the mesh with certain opening sizes. In this study, a dry pluviation device was designed and manufactured to examine the effect of shutter properties, including the height of fall (HF), deposition intensity (DI), and gradation on relative density (RD). A two-piece mold was used to evaluate the homogeneity of the sample. The RD measured at the top and bottom of the mold is the same, indicating that the fabricated sample is homogeneous. The results indicate that HF and DI have a direct and indirect relation with RD, respectively, but RD is constant for HF≥1200 mm. In order to investigate the impact of shutter properties on DI and RD, α ratio (total area of the shutter holes to the area of the deposition surface) was defined, and a linear relationship is proposed between DI and α. The results revealed an indirect relation between RD and α, but for α≥0.130, RD is constant. In order to assess the simultaneous effect of grain size and shutter properties on RD, an independent grain size variable (i.e., α/D50) was defined, and a linear relationship was established between α/D50 and RD. The results showed that the variable α/D50 can be considered a useful criterion for designing a shutter to reconstitute sandy soils with different gradations.

Keywords
Dry pluviation, Shutter porosity, Relative density, Deposition intensity

List of notations

HF:	is the height of fall
DI:	is the deposition intensity
RD:	is the relative density
ASH:	is the total area of the shutter holes
ADS:	is the area of the deposition surface
α:	is the total area of the shutter holes to the area of the deposition surface
D50:	is the median diameter or the medium value of the particle size distribution
D10:	is the effective size
C_C	is the curvature coefficient
Cu	is the uniformity coefficient
e_{max}:	is maximum void ratio
e_{min} :	is minimum void ratio
A_{SH}:	is the total area of the shutter holes
A_{DS}:	is the area of the deposition surface

Introduction

Physical modeling is one of the methods widely applied in laboratory studies. In this method, sample preparation is a critical step because of its effects on the outcomes of laboratory tests. Sample preparation methods should have the ability to reconstruct a natural soil fabric, a natural soil density, and a uniform void ratio (Arthur and Menzies, 1972; Oda, 1972; Yamamuro and Wood, 2004; Amini and Qi, 2000). Yin et al. (2019) studied the influence of sample preparation on the multi-scale structure of sand-clay mixtures. Moreover, sample preparation techniques can affect the fabric and stress-strain response of the soil particles (Tabaroei et al., 2017). The most common methods for sample preparation in physical modeling in laboratory studies include dry and wet moist tamping, dry and wet pluviation, mist pluviation, slurry deposition, dry funnel deposition, water sedimentation, and vibration (Lade and Yamamuro, 1997; Garga and Zhang, 1997; Wood et al., 2008; Tatsuoka et al., 1986; DeGregorio, 1990; Huang et al., 2015, Yin, 2021, Yin et al., 2021a, Yin et al., 2021b). Wichtman et al. (2020) investigated the impact of the sample preparation method on the cumulative strains in sand under high-cyclic loading. Mahmudi et al. (2020) prepared the samples using dry funnel pluviation and wet deposition at three selected relative densities and studied the impact of packing density and overconsolidation ratio effects on the mechanical response of granular soils. Wang and Brennan (2019) used the dry pluviation method for fiber-reinforced sand in centrifuge testing. Le et al. (2020) used air pluviation and dry vibration methods for soil preparations that investigated the effect of inherent anisotropy on the shear strength and shear modulus of both saturated and unsaturated. Khari et al. (2019) used the pluviation method and produced loose and dense sand samples with 30% and 75% relative densities. The slurry and dry tamping sample preparation can be employed in geotechnical engineering tests at the macroscopic scale, as microscale phenomena weakly affect the macroscopic response. These two methods do not affect the overall trend of soil-concrete interface friction angle versus clay content. Dry tamping leads to higher peak interface friction angles than slurry at low clay content. Also, the critical friction angle is not significantly modified when changing the sample preparation (Yin, 2021).

Selecting the most suitable method for sample preparation is difficult because each method has unique characteristics (Raghunandan et al., 2012). Among the mentioned methods, moist tamping and dry pluviation are used more frequently than other methods for sand sample preparation in large-scale models (Been et al., 1987; Pournaghiazar et al., 2011; Lombardi and Bhattacharya, 2014; Choi et al., 2010; Dave and Dasaka, 2012; Gade and Dasaka, 2015).

Vaid and Sivathayalan (2000) showed that reconstituted sandy soil samples retrieved by water pluviation closely mimic stress-strain behavior with undisturbed samples. Kuerbis and Vaid (1988) stated that the slurry deposition can produce a homogeneous sample with a fabric similar to natural fluvial sands. Sample preparation by wet pluviation produces the fabric of fluvial and hydraulic-fill sands (Oda et al., 1978; Vaid et al., 1999). Wood et al. (2008) demonstrated the declining effect of the sample preparation method on undrained behavior by increasing the density. Yin et al. (2021c) proposed a motivated choice of a preparation method for artificial clayey materials to be used in laboratory experiments. They prepared the sand-clay mixture samples with the three methods and showed that the samples were homogeneous at the macroscopic scale. Dry pluviation and water sedimentation methods produce sand samples with homogeneous density (Vaid et al.,1999). Also, it has been found that specimens reconstituted by moist tamping are less homogeneous compared to those prepared by dry pluviation. Dry pluviation is a sample preparation method based on the deposition of sand rained from a certain height. This method is widely used in physical modeling for reconstituting sand specimens of different sizes and widely adopted for the preparation of large, uniform, and repeatable sand beds of desired densities for laboratory studies to simulate in-situ conditions and obtain highly reliable test results (Dava and Dasaka, 2012). Jacobsen (1976) conducted comprehensive studies on dry pluviation techniques for large-scale physical models. He suggested that this method is capable of creating soil layers with a relative density (RD) between 20% and 90%, large thickness (about 1m), and homogenous dry densities (between 0.8-1.2%) at the top and bottom. This method can prepare sand samples with 100% RD (Rad and Tumay, 1987; Miura and Toki, 1982). In this regard, Rad and Tumay (1987) confirmed that specimens formed by this method are homogeneous. Moreover, it has been found that using this method for well-graded sand samples containing significant amounts of fines, particle segregation occurs in the reconstituted specimens (Vaid and Negussey, 1988; Wood et al., 2008). Overall, the dry pluviation method is suitable for reconstituting clean sandy soils with minimum particle segregation (Rad and Tumay, 1987). The advantages of this method compared to the vibration (ASTM D 4253-83) are a higher dry density, no particle crushing, less effect of segregation, and better repeatability (Lo Presti et al., 1993). Kim and Seo (2019) investigated void ratios of binary sand mixtures deposited by dry pluviation with various weight fractions of smaller particles and particle size ratios.

In the dry pluviation method, the density of the samples depends on the deposition intensity (DI), height of fall (HF), uniformity of raining sand, the opening width of the curtain in the curtain technique, the porosity of diffuser, particle size, and other parameters (Butterfield and Andrawes, 1970; Rad and Tumay, 1987; Vaid and Negussey, 1988; Lo Presti et al., 1992 &1993; Fretti et al., 1995; Lagioia et al., 2006; Choi et al., 2010; Raghunandan et al., 2012; Dave and Dasaka, 2012; Gade and Dasaka, 2015; Hariprasad et al., 2016; Srinivasan et al., 2016; Tabaroei et al., 2017). In general, an increase in DI leads to a decrease in the density of the soil specimen because with an increase in DI, the grains collide with each other increase, and the grains are farther apart, so the density decreases. The DI depends on shutter porosity as a function of hole size and hole spacing (Rad and Tumay, 1987). The height of fall (HF) is the distance between the lowest diffuser bottoms to the surface of the sand in the specimen (Choi et al., 2010; Gade and Dasaka, 2015). Deposition intensity (DI) is the mass of soil falling in the container per unit of area to per unit of time (Lo Presti et al., 1993; Dave and Dasaka, 2012; Gade and Dasaka, 2015). Shutter porosity is calculated as the hole area's ratio to the sand-raining hopper's total area (Okamoto and Fityus, 2006). The hole area includes single or multiple circular or rectangular holes. Increasing the shutter porosity is accompanied by an increase in DI and a decrease in RD. However, there is no statistically significant relationship between shutter porosity and DI (Okamoto and Fityus, 2006). Previous studies have reported an increase in density by increasing the HF and have shown the limited effect of HF. This limitation has been reported to be 500 mm from the top of the split mold sample (Okamoto and Fityus, 2006). Vaid and Negussey (1988) showed that the velocity of sand particles increases with an increase in HF until the critical velocity is reached, while a further increase in HF certainly would not affect the RD of the specimen. For a certain HF, an increase in DI increases the void ratio and decreases the RD of the sand sample (Rad and Tumay, 1987; Miura and Toki, 1982; Lo Presti et al., 1992 &1993; Fretti et al., 1995).

The diffuser is utilized to uniform sand rain. Researchers have used one or more sieves for this purpose (Jacobsen, 1976; Miura and Toki, 1982) and shown that sieves with smaller openings provide a more dispersed sand rain. Moreover, the number of sieves used in a diffuser and the distance between them have a negligible effect on the relative density (Rad and Tumay, 1987). Khari et al. (2014) designed a mobile pluviator that adopted the air pluviation method for the deposition of sand samples. Zakir Hossain and Ansary (2018) developed a portable traveling pluviator device and its performance to prepare uniform sand specimens.

This paper aims to study factors that are effective in DI by controlling the shutter characteristics for three types of sandy soils with different grain size distributions. Also, it introduces a new criterion for designing a shutter to reconstitute a sample with the desired relative density.

Materials and methods

This study used three different gradations of sandy soils (S1, S2, and S3) with less than 10% fine content. These sandy soils contain 97.5% SiO_2, 0.85% Fe_2O_3, 0.95% Al_2O_3, and 0.7% other oxides. Index properties of the soils used in this study are shown in Table 1. D_{10}, D_{50}, C_c, and C_u values were determined for each sample from the particle size distribution curve. The particle size distribution (gradation) test, the maximum and minimum voids ratio test, and the determination of specific gravity of solid grains test were conducted according to the standards of D6913, D4253, D4253, and D854, respectively.

Table 1. Index properties of sandy soils S1, S2, and S3

Sample ID.	USCS	Gs	D_{50}	D_{10}	Cu	Cc	e_{min}	e_{max}
S1	SP	2.62	1.64	0.79	2.27	1.29	0.40	0.77
S2	SP	2.65	0.50	0.12	5.6	0.79	0.43	0.74
S3	SP-SM	2.70	0.18	0.08	2.73	0.97	0.55	0.91

Figure 1 presents particle size distribution curves of these soils compared with the size distribution curves of soils used by other similar researchers. The soil ranges used by other (not similar) researchers are represented by dashed lines. This figure illustrates that the three sandy soils used in the present study cover all gradation ranges of soils used for sample preparation using the dry pluviation method.

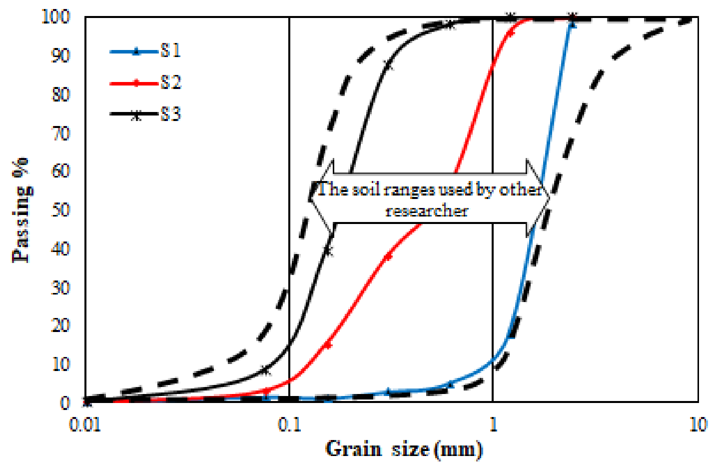
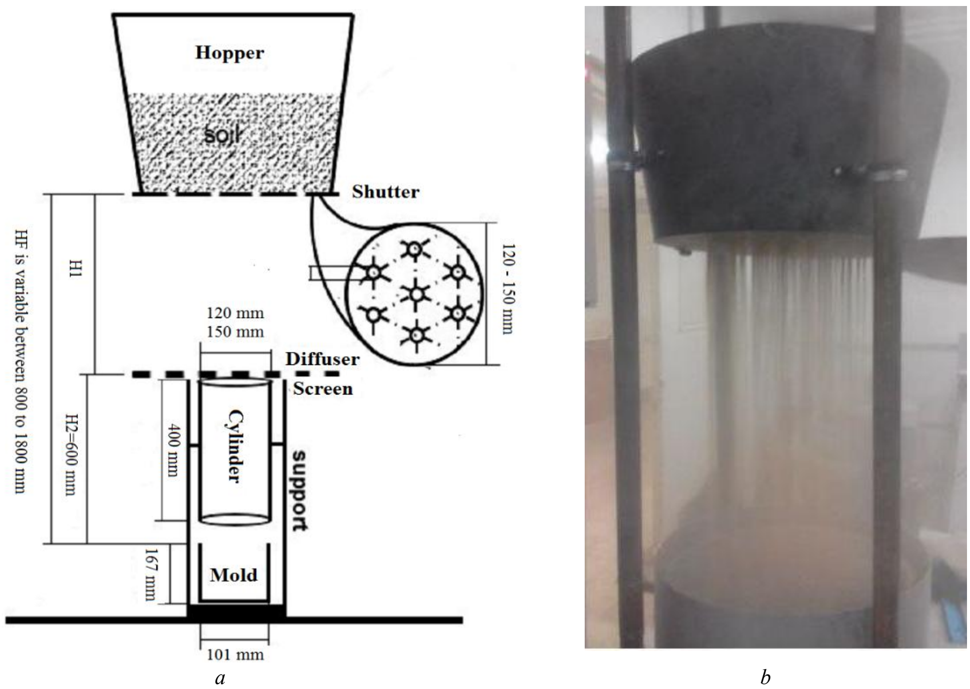


Figure 1. Particles size distribution of sandy soils in this study and soils used by some researchers such as Been et al., 1987; Pournaghiazar et al., 2011; Lombardi and Bhattacharya, 2014; Choi et al., 2010; Dave and Dasaka, 2012; Gade and Dasaka, 2015; Wang and Brennan, 2019; Khari et al., 2019.

The dry pluviation apparatus used to prepare sand samples in this study is shown in Figure 2. This equipment includes a hopper with a height of fall (HF) up to 1800 mm, a shutter with a triangular hole pattern, a single diffuser screen, and a cylinder for uniform column sand raining. The diameter of holes and shutter porosity are between 8-15 mm and 0.4-13.9% separately (Table 2). The distance between the shutter and diffuser screen is denoted by 'H_1'. There is no device in this distance, and the distance between the diffuser screen and the top of the mold is shown with 'H_2' which is variable during pluviation as the soil surface moves up; the height of fall is $HF=H_1+H_2$. The mold used is a two-piece that can control the RD homogeneity; considering that the RD of the sample in the upper and lower part of the mold is the same, it can be concluded that the sample prepared by this method is uniform and homogenous. Detailed specifications of the apparatus are presented in Figure 2. In all tests, to achieve the maximum RD, the sand was rained from the hopper and through shutter holes, passing a single diffuser screen placed at a distance of 600 mm (H_2=600 mm) from the top of the mold. The Diameter of the shutter plate and mold (as shown in Figure 2 and Table 2) are between 120 - 150 mm and 101 mm separately, so the ratio shutter diameter/mold diameter is between 1.2-1.5.



a b

Figure 2. The pluviation apparatus a) details specification, b) actual photo (There is no device between the shutter and the diffuser)

Deposition intensity (DI) was calculated by measuring the mass deposited in the mold during a specified time. A change in DI resulted in the consequent changes in hole size, hole spacing, and the number of holes. Table 2 presents the values assigned to these variables.

The holes were arranged in a triangular pattern. Two diffuser screens with mesh numbers #4 (for sample S1) and #8 (for samples S2 and S3) were used (ASTM E11:01). To avoid the dispersal of sand and provide a route for precipitation, cylinders with 150 and 120 mm diameters were embedded in the distance between the diffuser screen and split mold.

Table 2. The summary of the test designs and results

Sample ID.	D50 (mm)	Hole diameter in shutter (mm)	Number of holes	Cylinder diameter rainfall (mm)	α ratio	α/D50 (1/mm)	Deposition intensity (DI, kg/min/m^2)	Relative density (RD, %)
S2	0.5	8	1	120	0.004	0/008	68.41	94
			2		0.009	0/018	142.67	93
			4		0.018	0/036	282.01	92
			7		0.031	0/062	393.42	94
			1	150	0.003	0/006	54.15	95
		10	1	120	0.007	0/014	128.84	94
			2		0.014	0/028	274.08	94
			3		0.021	0/042	375.15	92
			7		0.049	0/098	1004.14	93
			19		0.132	0/264	2236.07	72
		12	1	120	0.010	0/020	194.35	95
			2		0.020	0/040	390.92	94
			3		0.030	0/060	601.50	92
			7		0.070	0/140	1427.77	85
			19		0.190	0/380	4055.20	67
		15	1	120	0.016	0/032	369.35	94
			2		0.031	0/062	446.41	92
			3		0.047	0/094	1112.44	88
S3	0.18	8	1	120	0.004	0/022	85.93	95
			1	150	0.003	0/017	53.91	96
			2	120	0.009	0/050	156.93	95
			4		0.018	0/100	314.87	93
			7		0.031	0/172	549.51	85
		10	1	120	0.007	0/039	159.58	93
			3		0.021	0/117	419.93	87
			7		0.049	0/272	941.62	65
			19		0.132	0/733	3192.93	38
		12	1	120	0.010	0/056	209.95	91
			2		0.020	0/111	393.74	87
			3		0.030	0/167	593.83	84
			7		0.070	0/389	2056.5	55
			19		0.190	1/056	4786.94	37
		15	1	120	0.016	0/089	380.56	87
			2		0.031	0/172	706	75
			3		0.047	0/261	1076.89	67
S1	1.64	10	1	120	0.007	0/004	75.60	95
			2		0.014	0/009	126.37	91
			3		0.021	0/013	195.99	90
			7		0.049	0/030	674.02	83
			19		0.132	0/080	1189.98	84
		12	1	120	0.010	0/006	109.56	90
			1	150	0.006	0/004	109.77	92
			2	120	0.020	0/012	202.30	86
			3		0.030	0/018	270.87	86
			7		0.070	0/043	947.29	85
			19		0.190	0/116	2168.06	81
		15	1	120	0.016	0/010	264.12	87
			2		0.031	0/019	473.73	88
			3		0.047	0/029	615.49	84

Test results

The relation between 'HF' and 'RD'

To investigate the effect of HF on RD, sample S3 was selected. In these test series, H_1= 600 mm, and H_2 is variable between 200 to 1200 mm. Therefore, in this part of the research, which examines the effect of HF on RD, the HF varies between 800 to 1800 mm. In Figure 3, variations of RD with HF are plotted for three different DIs.

HF and RD have a direct relationship, and as HF increases, RD increases as well, but when HF≥1200 mm, RD remains constant. Besides, for a specific HF, with an increase in DI, RD decreases. On the other hand, there is a direct relationship between shutter porosity and DI. Therefore, with increasing shutter porosity, DI increases, and RD decreases. Since HF≥1200 mm has no effect on RD, experiments were performed with HF=1200 mm to investigate the precipitation rate in the next research sections.

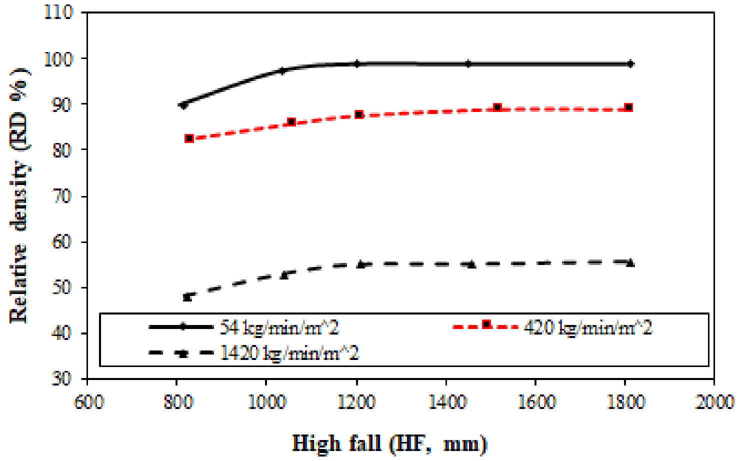


Figure 3. RD versus HF for three different DI for sample S3

The relation between 'HF' and 'DI'

The deposition intensity (DI) is defined as the mass of soil that enters the mold per unit of time. Figure 4 illustrates DI versus HF in two different conditions. In case 'a', there is a cylinder between the diffuser screen and mold, and in case 'b', there is no cylinder between the diffuser screen and mold. In case 'a', with an increase in HF, DI is uniform and constant, while in case 'b', with an increase in HF, DI starts to decrease. In case' b', due to the absence of the cylinder, the sand grains are separated and dispersed after passing through the diffuser screen, so DI decreases and is variable.

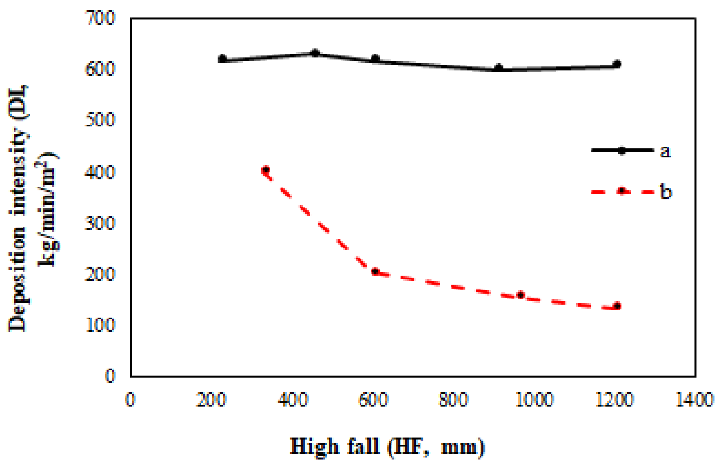


Figure 4. DI versus HF a) with the cylinder and b) without the cylinder

Therefore, in all tests in this study, a cylinder was used to achieve a uniform deposition intensity. Figure 4 shows that the deposition surface and shutter hole size controls DI. To determine the simultaneous effect of the hole size and the deposition surface, parameter' α' was defined by equation 1.

$$\alpha = \frac{The\ total\ area\ of\ the\ shutter\ holes}{The\ area\ of\ the\ deposition\ surface} = \frac{A_{SH}}{A_{DS}} \quad (1)$$

The total area of the shutter holes (A_{SH}) is calculated from the sum of holes existing in the area of the shutter. The deposition surface (A_{DS}) is described as sand passing through a cylinder embedded between the diffuser screen and mold (i.e., the area of the cylinder).

For example, in Figure 2, there are 7 holes, each with a 10 mm diameter in the surface area; so, A_{SH} =542.5 mm^2, the cylinder diameter is 120 mm, and A_{DS} =11304 mm^2. According to Eq. 1, α is calculated as follows:

$$\alpha = \frac{542.5\ mm^2}{11304\ mm^2} = 0.049 \qquad (2)$$

The experimental design of this study includes measuring DI in the specified shutter porosity calculated by equation 1. Table 2 presents the α ratio estimated using equation 1 for the whole tests.

Using the data presented in Table 2, Figure 5 illustrates the correlation between the α ratio and the DI for various soil gradations. As can be seen in this figure, there are linear relationships between the α ratio and DI for all samples.

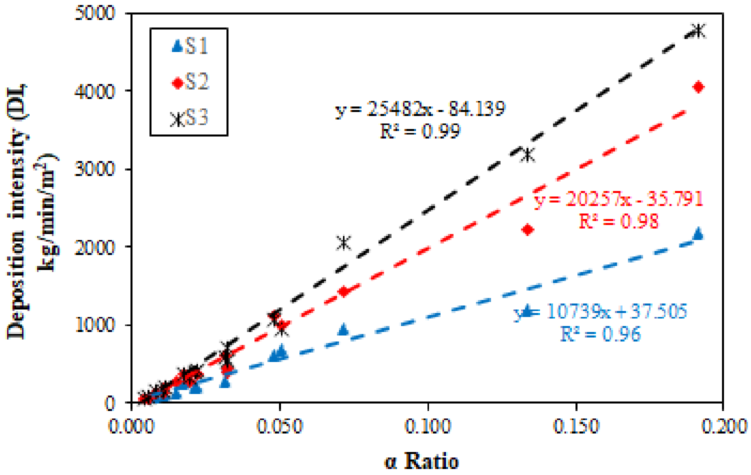


Figure 5. DI versus α ratio for 3 sand samples (S1, S2, and S3)

According to the determination coefficients (R^2) presented in Figure 5, it can be stated that the α ratio is a comprehensive criterion for estimating the DI. As the α ratio increases, the DI increases. Also, it has been shown that DI is variable at the constant α ratio for sandy soils with different gradations. Under the same conditions, sandy soil with smaller gradation shows a higher DI. This effect is greater in a higher α ratio. In other words, the DI depends on soil gradation in the same conditions as the shutter.

In the tests conducted on sand S1, it was observed that pluviation was stopped in the hole diameter of 10 mm because the grain of soil accumulates in the shutter holes. The accumulation of sand grains on the shutter is a function of D_{50} and the hole diameter. In this test "hole diameter/D_{50}" ratio was 6.1. In the other tests, this ratio was greater than 6.1, and no grain accumulation occurred on the shutter. Thus, it is suggested that the minimum hole diameter is 7 times more than the D_{50} of soils.

The relation between 'RD' and 'DI'

The results in Table 2 were used to study the effect of DI on RD for sandy soils. Based on the data in Table 2, Figure 6 presents the RD plotted versus DI for three soil samples. These results confirm that RD decreases with an increase in DI. Also, it was observed that RD for the same DI depends on soil gradation. For example, in soil S3 (D_{50} =0.18 mm) for DI≥3200 (kg/min/m^2), an increase in the DI does not affect the RD, while in soil S1 (D_{50}=1.64 mm) and S2 (D_{50}=0.5 mm) for DI≥1190 (kg/min/m^2) and DI≥2250 (kg/min/m^2) respectively, an increase in the DI does not affect the RD.

Based on Figure 5, there is a significant relation between α ratio and DI. Moreover, based on Figure 6, there is a relation between DI and RD, so the α ratio can serve as a useful parameter for evaluating RD. Figure 7 depicts the relationships between the α ratio and RD for sandy soils. The results confirm that RD decreases with increasing the α ratio. The figure also presents the effect of soil gradation on the DI under the same device conditions. As can be noted, the α ratio greater than 0.130 has almost no effect on RD.

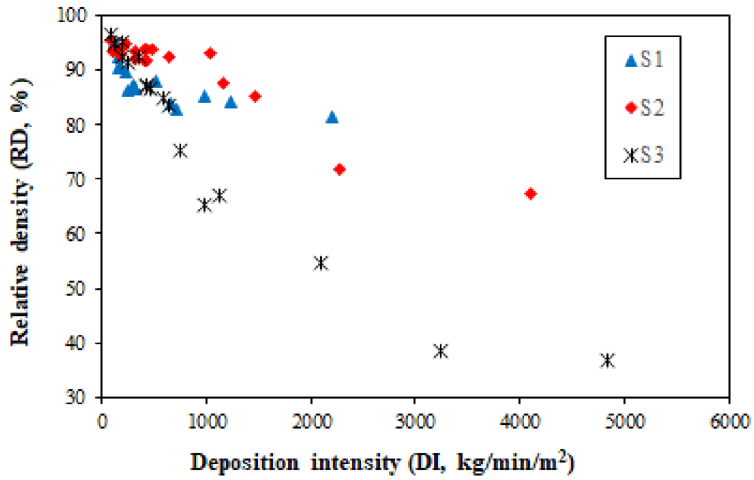


Figure 6. The relationships between DI and RD for sand samples (S1, S2, and S3)

There is a limitation for α ratio as a device parameter such that for α ratios greater than 0.130, the DI does not affect the RD. For $\alpha \leq 0.130$, it is suggested that samples with lower RD are obtained by adjusting the HF and increasing the diffuser sieve opening. The results show that RD depends on soil gradation, H_2, and the α ratio as a device parameter (Figure 7). A new parameter (i.e., α/D50) was used to remove soil gradation's effect on the results. Figure 8 shows a linear relationship (R^2 =0.86) between α/D_{50} and RD for sand samples S1, S2 and S3. Due to the above-mentioned limitation for α, the data α>0.130 has been omitted in this relationship.

The most important feature of Figure 8 is the simultaneous assessment of soil gradation, hole area, and deposition surface on RD. According to Figure 8, Equation 3 to design shutter properties for sandy soils can be presented:

$$RD = -64.929\frac{\alpha}{D_{50}} + 95.99 \qquad (3)$$

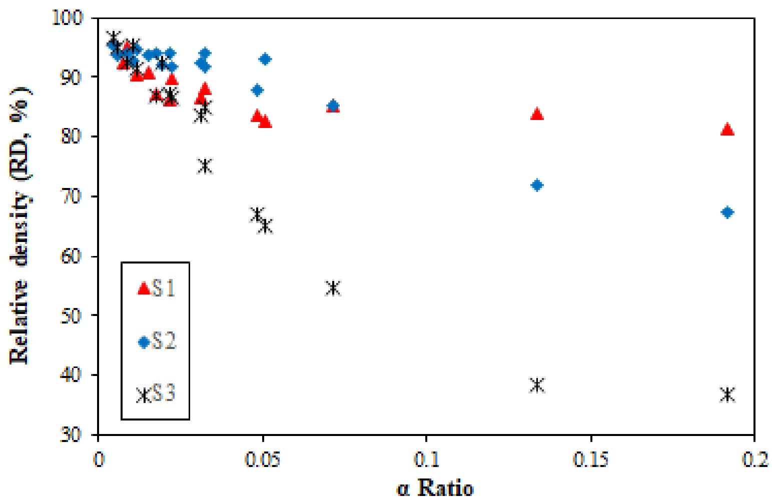


Figure 7. The relationships between the α ratio and RD for sand samples (S1, S2, and S3)

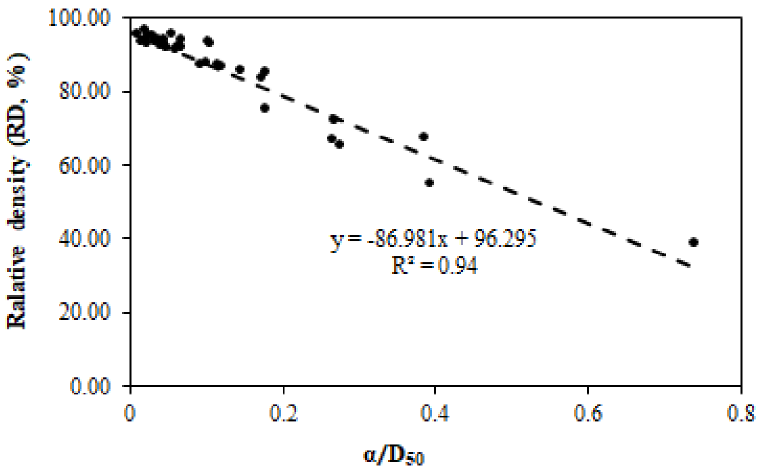


Figure 8. The relationships between α/D50 and RD for sand samples (S1, S2 and S3)

Discussion

This research was conducted to evaluate some parameters affecting dry pluviation in three sand samples with different grain size distributions. Based on previous studies, the RD range of samples made with the dry pluviation method is 20%≤RD≤90% (Jacobsen, 1976) and RD=100 (Rad and Tumay, 1987; Miura and Toki, 1982; Okamoto and Fityus, 2006). In this research, samples were produced with 45%≤RD≤100%, suggesting that it allows preparing samples with different RD values.

In this study, a two-piece mold was used to evaluate the homogeneity of the sample. The RD at the top and bottom of the mold are the same, so we can say the fabricated sample is homogeneous. The preparation of homogeneous samples using this method has already been reported by Jacobsen (1976) and Rad and Tumay (1987). This research found that for HF≥1200 mm, RD is not dependent on the HF and is constant throughout the sample. Therefore, to prepare uniform RD samples, the HF was considered to be 1200 mm.

In this study, similar to previous works, it was observed that the RD of the samples depends on the deposition intensity (DI), the height of fall (HF), the porosity of the diffuser, and particle size. Okamoto and Fityus (2006) showed that with an increase in the shutter porosity, DI increases while RD decreases. However, no statistically significant relationship between shutter porosity and the DI was extracted. In this research, the α ratio (A_{SH}/A_{DS}) was defined to assess the impact of shutter properties on DI and RD. A linear relationship was proposed between DI and α with R2≥0.86 for each particle's size. The results revealed an indirect relation between RD and *α*. Moreover, it was found that for α≥0.130, RD is constant. The range of α variations in the present study is between 0.003 and 0.19.

Several studies have shown that with an increase in the HF, the velocity of sand particles increases until the critical velocity is reached, while a further increase in HF certainly would not affect the RD of the specimen (Vaid and Negussey, 1988). This limitation has been reported for a height of 500 mm from the top of the split mold sample (Okamoto and Fityus, 2006). In this study, the direct relation between the HF and RD was established, but for HF≥1200 mm, RD is constant and independent of the HF.

In this study, similar to previous works (Rad and Tumay, 1987; Miura and Toki, 1982; Lo Presti et al., 1992 &1993; Fretti et al., 1995), we observed that for a certain HF, an increase in DI leads to a decrease in RD of the sand sample. The results of this study revealed that HF and DI have direct and indirect relations with RD, respectively, and for HF≥1200 mm, RD is constant for a further increase in HF. In addition, RD was constant with DI. To analyze the simultaneous effect of shutter properties and grain size, we proposed a new parameter (α/D_{50}) and presented a linear relationship between RD and α/D_{50}.The range of D_{50} and α/D_{50} variations in the present study are $1.8 \leq D_{50} \leq 1.64$ and $0.006 \leq \alpha/D_{50} \leq 0.8$ separately.

Conclusion

In this study, a dry pluviation apparatus was fabricated. Then, three soils with various gradations were used, and the effect of different factors, such as shutter properties and gradation, on the DI and relative density (RD) was investigated. Overall, the results of the present study can be summarized as follows:

- HF and RD have a direct relationship; as HF increases, RD increases as well, but RD remains constant when HF≥1200 mm.

- The relationship between DI and HF, as well as shutter properties, are a function of the deposition surface. In order to investigate the simultaneous effect of these two variables, a new parameter (α ratio) was defined.
- There are direct linear relationships between the *α* ratio and DI for three samples studied in this research. In addition, this relation is associated with soil gradation.
- With an increase in DI, RD decreased, but RD is almost constant for a specified DI, with an increase in DI. In the dry pluviation apparatus made in the present study, the specified DI for soil S3 is equal to 3200 $kg/min/m^2$. Also, it was observed that in the same DI, RD depends on soil gradation.
- There is a relation between RD and α ratio. With an increase in *α* ratio, RD declines, but RD is almost constant, exceeding a specified *α* ratio (i.e., 0.13). Moreover, RD for the same *α* ratio was observed depending on soil gradation.
- In order to remove the effect of soil gradation on RD, a new parameter (i.e., α/D_{50}) was defined. The main feature of this parameter is the simultaneous investigation of the shutter specification and soil gradation. There is a linear relation between RD and α/D_{50}. The results revealed that the parameter α/D_{50} is a comprehensive criterion for estimating the DI required for sample preparation and shutter design.
- It is recommended to prevent the accumulation of particles by considering the minimum hole size 7 times greater than the D_{50} of soils.
- In this step of the study, we have not used this method to prepare the physical model. While the proposed parameters in the present study are dimensional-independent, large sample preparation must be used with caution.

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