FACTORS INFLUENCING VIBRATORY COMPACTION OF COHESIONLESS SOILS

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Field data are given for 22 test fills made of medium-to-fine uniform sand and compacted by 7 models of vibratory compactors. The final relative density is correlated with lift thickness, number of coverages, total static plus dynamic force applied by the compactor, towing speed, and operating frequency. There is considerable scatter in these correlations because of difficulties in determination of in situ relative density, heterogeneity in the degree of compactness of sand, variation of the depth at which the relative density is determined, and lack of sufficient data when a single variable is studied and other variables are fixed. However, the data indicate that the final relative density increases as operating frequency, total applied force, or the number of coverages increases. The variation in lift thickness up to 1 ft (0.3 m) has no significant effect on this density, but an increase in towing speed reduces it. A study of the trends of the relationships between final relative density and the various variables and a dimensionless and statistical analysis establish a correlation between the final relative density and a factor expressing the joint effect of the important properties of the soil, compactor, and compaction procedure. Such correlations, when available and justified, help in the choice of the compactor or compaction procedure for a given job.

•VIBRATORY compaction of cohesionless soils, used as early as the 1930s (1), is influenced by resonant frequency of compactor-soil system, number of load cycles, variation of shear strength during vibration, and magnitude of dynamic stresses generated by the vibrator.

Improvements in construction and construction efficiency are partially based on experience and well-documented studies. Full-scale field experiments are badly needed. This paper presents field data for 7 models of vibratory compactors used to compact 22 test fills made of medium-to-fine sand at the Pumped Storage Project at Ludington, Michigan (6).

The objectives of the analysis of the field test results are

1. To evaluate specific variables, such as lift thickness, number of coverages, total force applied by the compactor, operating frequency, and towing speed, that influence the final relative density of the compacted sand.
2. To explore feasible relationships between the final relative density and one factor that can express variations in compaction procedure, compactor characteristics, and properties of soil.

CONSTRUCTION OF TEST FILLS

Test fills were constructed of the site sand that is a light brown, uniform, medium-to-fine sand having a uniformity coefficient of about 2. It is classified as SP according

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to the Unified Soil Classification System. The overage value of the fraction passing the No. 200 sieve ranges, for the various test fills, is between 1.4 and 5.5 percent, and the representative value is 2.4 percent. Range of grain size distribution curves of this sand is shown in Figure 1. The average placement water content for the sand in the various test fills varied between 1.1 and 6.1 percent and averaged close to 4.2 percent.

Each test fill had plan dimensions of 30 by 160 ft (9 by 49 m). There were four to eight lifts, and the compacted lift thickness varied from 0.45 to 1.00 ft (0.14 to 0.3 m). Test pits were made at about 6 or 9 ft (1.8 or 2.7 m) from the centerline of the test fill.

The in situ density after compaction was determined at depths of 1.25, 2.25, and 3.25 ft (0.4, 0.7, and 0.99 m) by using the water balloon and sand cone methods. In each test fill, from 8 to 49 tests (an average of 30 tests) were performed. The total number of tests performed in the test fills was 663.

The final relative density D_r (ASTM D2049) for each test fill, after compaction, is given in Table 1.

TECHNICAL DATA FOR VIBRATORY COMPACTORS

Vibratory compactors in these tests were all towed by a tractor at speeds between 1.5 and 4.5 mph (2.4 and 7.2 km/h) (Table 1). They can be classified according to their static weights as follows (1 T = 0.9 t):

Compactor Type	Static Weight (ton)
Light	<2
Medium	2 to 4
Heavy	4 to 7
Very heavy	>7

All the vibratory compactors used in this investigation are, according to this classification, either heavy or very heavy.

The vibrations of the roller or drum are produced by an eccentric weight mounted on a rotating shaft within the drum. The frequency of the rotating shaft can be altered by a throttle setting. The operating frequency of the compactors varied between 1,100 and 2,250 vibrations/min.

Vibrations of the drum produce a centrifugal dynamic force F_{dyn} that depends on the weight and eccentricity of the eccentric weight in the drum and also on the square of the maximum operating frequency of the vibration. The sum of the static weight of the compactor and its dynamic force is the total applied force. In general, the total applied force by tractor-towed compactors is two to three times the static weight of the vibrator (1).

A summary of the available technical data for the compactors used in the test fills is given in Table 2.

FIELD TEST RESULTS

There are two ways to present the field test results. The first is to determine the influence of one variable only on the final relative density while all other factors are kept constant. The second is to study the influence of one variable on the final relative density regardless of the variation in the other variables. The first approach is scientifically accepted. The second approach indicates the general trend and probably the overriding influence of the variable under consideration. In Figures 3 and 6, a refers to the first approach and b refers to the second approach. It is natural that, in general, the scatter in Figures 3b and 6b is much greater than that in Figures 3a and 6a.

Figure 1. Grain size curves for site sand.

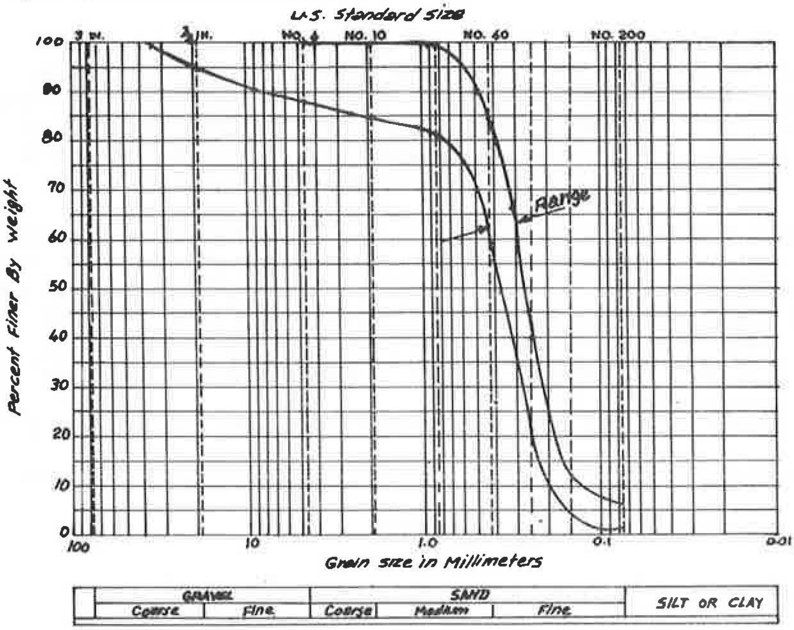


Table 1. Vibratory compaction field test data from test fills at Ludington, Michigan.

Compactor Model[a]	Lift		Number of Coverages	Towing Speed (mph)	In Situ Density Test		Final D_r (percent)
	Number	Thickness[b] (ft)			Type	Number	
CF-43	4	1.00	3	1.5	SC[c], W[d]	22	80
CF-43	4	1.00	6	1.5	SC, W	23	79
CF-43	8	1.00	6	1.5	SC, W	23	91
CF-43	4	1.00	10	1.5	SC, W	20	88
VP-22D	4	1.00	3	1.5	SC, W	20	87
VP-22D	4	1.00	6	1.5	SC, W	20	79
VP-22D	4	1.00	10	1.5	SC, W	8	98
CH-43	5	1.00	6	1.5	SC, W	20	92
CF-43	5	1.00	6	1.5	SC, W	22	86
RVT-200	4	1.00	6	1.5	SC, W	22	96
CH-43	4	1.00	6	1.5	SC, W	22	90
CF-43	4	1.00	6	3.0	W	30	80
CF-43	4	1.00	6	4.5	W	30	81
VP-22D	4	1.00	6	3.0	W	27	97
SV-70	4	1.00	6	1.5	W	27	90
CF-43	8	1.00	6	1.5	W	40	101
RVT-100	8	0.55	6	1.5	W	47	88
CF-43	8	0.45	6	1.5	W	47	90
RVT-100Z	8	0.70	6	1.5	W	48	92
CF-43	8	0.77	6	3.0	W	49	87
RVT-100Z	8	0.72	6	3.0	W	48	98
RVT-100	8	0.68	6	3.0	W	48	85

Note: 1 ft = 0.3 m. 1 mph = 1.6 km/h.

[a] Table 2 gives data on compactors.

[b] After compaction.

[c] Sand cone method.

[d] Water balloon method.

Table 2. Technical data for vibratory compactors used in test fill.

Type	Model	Drum Width (in.)	Drum Diameter (in.)	Foot Length (in.)	Vibrating Power (hp)	Operating Frequency (cycles/min)	Static Weight (lb)	Dynamic Force[a] (lbf)	Total Force[a] (lbf)
Smooth drum	VP-22D	78	60	–	66	1,100 to 1,300	22,750	41,400	64,150
	RVT-100	76	56	–	55	1,350 to 2,250	13,500	33,000	46,500
	RVT-200	76	56	–	73	1,350 to 2,250	17,800	40,000	57,800
	CH-43	75	47	–	30	1,400 to 1,600	10,000	23,000	33,000
Sheep's-foot	CF-43	75	47	7.9	30	1,400 to 1,600	12,000	23,000	35,000
	SV-70	75	49	7.2	74	1,500 to 1,800	14,500	30,850	45,350
	RVT-100Z	76	56	7.9	55	1,350 to 2,250	13,500	33,000	46,500

Note: 1 in. = 2.5 cm. 1 hp = 0.746 kPa. 1 lb = 0.45 kg. 1 lbf = 4.4 N.

[a] At maximum operating frequency.

Influence of Lift Thickness on Final Relative Density

The relationship between lift thickness and relative density for all test fills is shown in Figure 2. The range of lift thickness studied was 0.45 to 1.00 ft (0.14 to 0.3 m). The data indicate that, within the limits of lift thickness, the value of D_r did not vary as the lift thickness varied. This may be explained by the overvibration phenomenon (2) that occurs near the vibrated surface of each layer and that may tend, for small lift thicknesses, to compensate the increase in the degree of compactness of the sand for the reduction of the lift thickness.

Since the variation in lift thickness from 0.45 to 1.00 ft (0.14 to 0.3 m) did not influence the final relative density, it was more economical to use a 1-ft (0.3-m) lift thickness. Extension of this conclusion beyond a 1-ft (0.3-m) thickness is not appropriate.

Influence of Number of Coverages on Final Relative Density

The relationship of the number of coverages and D_r for all test fills is shown in Figure 3. The data show that the final relative density increases as the number of coverages increases. The rate of increase beyond six coverages was smaller than that from three to six coverages.

The increase in relative density that occurs as the number of coverages increases is expected and agrees with previously published data (5). The increase in number of coverages represents an increase in the compactive effort. However, when the sand gets dense enough, an increase in the compactive effort may not be effective enough to produce densification of the soil.

Influence of Total Force Applied by Compactor on Final Relative Density

The relationship between total applied force and D_r for all test fills is shown in Figure 4. An increase in this force causes an increase in the dynamic stress applied to the soil. This is an important factor in causing densification of the soil (2).

The data show an increase in D_r for a total force of 35,000 to 46,500 lbf (156 to 207 kN). An additional increase in the total force up to 64,150 lbf (285 kN) did not cause any further change in D_r.

Previous data show good correlations between degree of compaction and static weight per unit width of the roller (4).

Influence of Operating Frequency of Compactor on Final Relative Density

The frequency of the compactors used in this investigation varied from 1,200 to 1,800 cycles/min.

The relationship between operating frequency and D_r, shown in Figure 5, is for test fills in which only the frequency varied. Each lift in these fills received six coverages from compactors towed at 1.5 mph (2.4 km/h). The figure indicates that the final relative density increases as the frequency of the compactor increases.

Previous studies indicated that the increase in operating frequency up to 1,200 cycles/min caused an increase in D_r for medium-to-fine sand (2). For well-graded sand, dry density increased as frequency increased up to 2,400 cycles/min and then decreased as frequency further increased (5). This agrees generally with the relationship between frequency and dynamic force on the soil surface (1, 2).

Figure 2. Final relative density versus lift thickness.

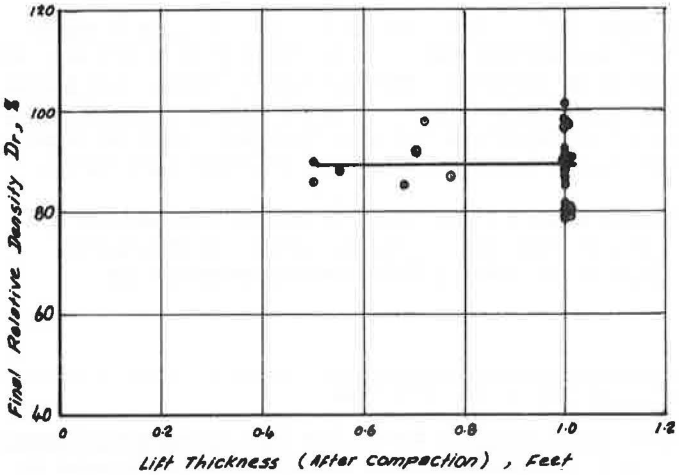


Figure 3. Final relative density versus number of coverages for (a) CF-43 vibratory compactors towed at 1.5 mph (2.4 km/h) and (b) various vibratory compactors and different towing speeds.

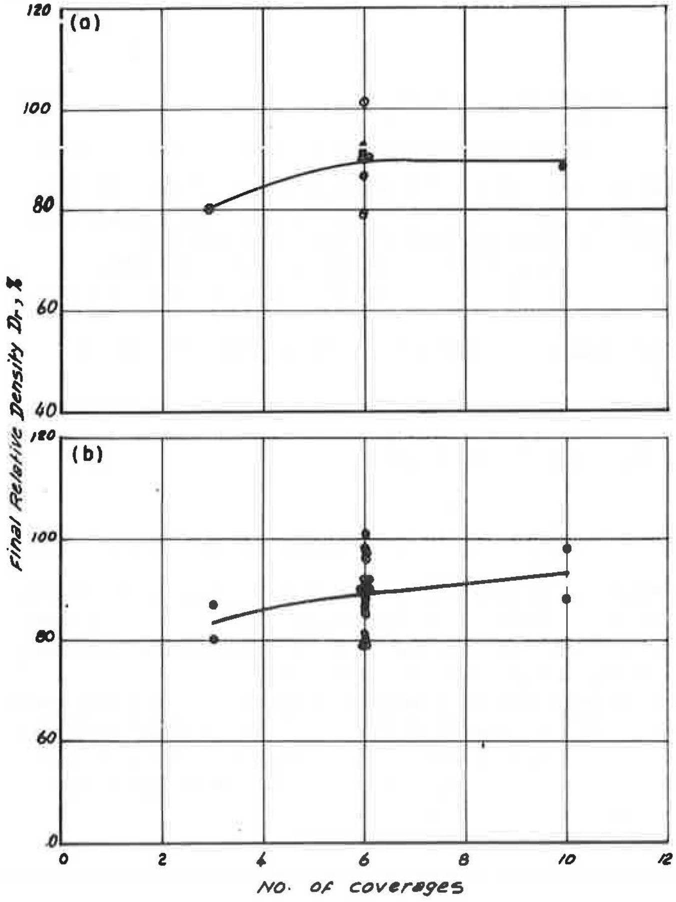


Figure 4. Final relative density versus applied force for various compactors and different towing speeds.

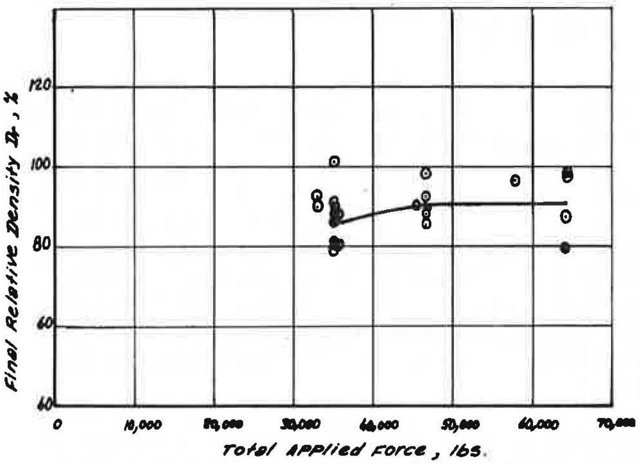


Figure 5. Final relative density versus operating frequency based on six coverages of vibrating compactors towed at 1.5 mph (2.4 km/h).

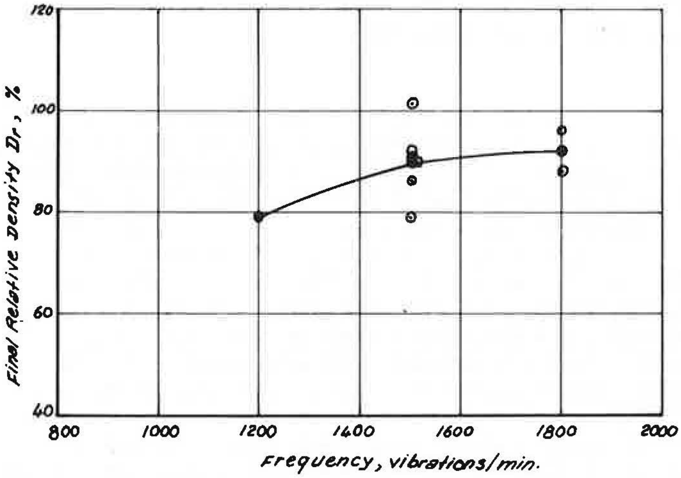
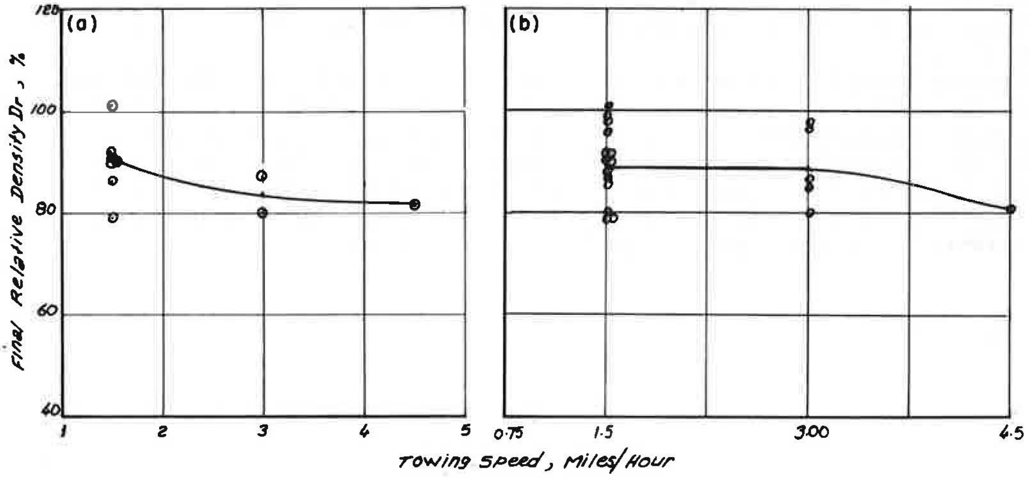


Figure 6. Final relative density versus towing speed for (a) test fills placed on 1-ft-thick (0.3-m) compacted lifts and (b) all test fills.



Influence of Towing Speed on Final Relative Density

The compactors were towed at speeds between 1.5 and 4.5 mph (2.4 and 7.2 km/h). Figure 6a shows the relationship of towing speed and D_r for test fills placed in 1-ft-thick (0.3-m) compacted lifts. Each lift received six coverages of vibratory compactors operating at a frequency of 1,500 cycles/min. The relative density decreases as the towing speed increases. A similar relationship, shown in Figure 6b, was obtained for all test fills. The lack of sufficient field data at a towing speed of 4.5 mph (7.2 km/h) is apparent; however, the relative density decreased when the towing speed increased beyond 3 mph (4.8 km/h). Thus, although the increase in towing speed is economically desirable, it causes a decrease in the final relative density. (Towing speed reflects the rest periods between the cycles if the frequency is the same.)

The increase that occurs in the final relative density as towing speed decreases agrees with previously published data (3).

The considerable scatter in the correlations shown in Figures 2 to 6 may be due to difficulties in determination of in situ relative density, heterogeneity in the degree of compactness of the sand, variation of the depth at which the relative density is determined, and lack of sufficient data when a single variable is studied while other variables are fixed.

CORRELATION OF SOIL PROPERTIES WITH COMPACTION PROCEDURE AND CHARACTERISTICS OF VIBRATORY COMPACTORS

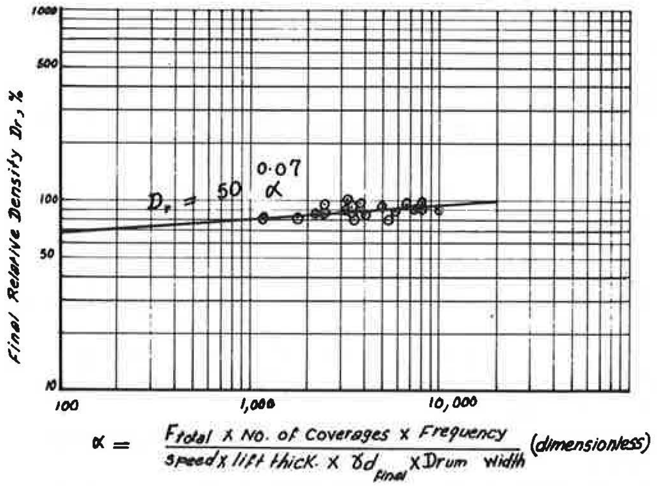
It is difficult to establish general guidelines for selecting vibratory rollers or compaction procedures for cohesionless soils. Many variables are involved that may have appreciable effect on the result of compaction. Some of these variables are associated with properties of the compacted soil such as the content of fines, initial dry density, placement water content and size, roughness, and gradation of particles. A second group of variables pertain to the technical data of the vibrator. For example, the static weight of the compactor, the mass and eccentricity of the eccentric weight in the drum, the maximum operating frequency of the shaft and, hence, the maximum centrifugal radial force, the drum width, and diameter may all affect compaction. A third group of variables is related to details of the compaction procedure such as the frequency of the rotation of the shaft, the number of coverages, the towing speed, the lift thickness, and the number of lifts.

The data from the test fills at Ludington, Michigan, present an opportunity to explore the feasibility of establishing some type of relationship among some of the factors involved in the compaction of cohesionless soils. From the first group of variables, the dry density of the soil was considered to be one of the variables that may reflect some of the other variables pertaining to the soil properties. From the second group of variables, the force per unit width of the drum was speculated to be an important variable (4). The main variables pertaining to the compaction procedure, namely frequency, number of coverages, towing speed, and lift thickness, were all considered in the analysis.

A good criterion that can be used for comparing the performance of the vibratory compactors in cohesionless soils is the final relative density of the compacted soil. Data shown in Figures 2 to 6, previously published data (1, 2, 3, 4, 5), and intuition suggest that this relative density should increase as total force (F_{total}) per unit width of drum, number of coverages, and frequency increase and as towing speed, lift thickness, and initial (or final) dry density of the soil decrease. A dimensionless relationship between D_r and these variables can be given in the form:

$$D_r = K \alpha^a \tag{1}$$

Figure 7. Final relative density versus dimensionless factor α.



where

K and a = constants, and

$$\alpha = \frac{F_{total} \times \text{number of coverages} \times \text{frequency}}{\text{speed} \times \text{lift thickness} \times \alpha d_{final} \times \text{drum width}} \tag{2}$$

The data available from the test fills at Ludington were used to calculate the values of α in equation 2. The variation in D_r in relation to α is shown in Figure 7 on log-log scale. Figure 7 shows that the proposed equation 1 is a good representation of the data. A statistical study of the data shown in Figure 7 gives K = 50 and a = 0.07. Thus the data obtained from the test fills constructed of poorly graded medium-to-fine sand at Ludington, Michigan, lead to the following relationship between α and D_r:

$$D_r = 50\ \alpha^{0.07} \tag{3}$$

CONCLUSIONS

1. Relative density can be used as a measure of the effectiveness of various variables involved in the vibratory compaction of cohesionless soils.
2. For the poorly graded medium-to-fine sand used in the test fills at Ludington, Michigan, the following are valid: (a) The variation of the compacted lift thickness between 0.45 and 1.00 ft (0.14 to 0.3 m) did not significantly influence D_r, (b) D_r increased as the number of coverages (up to six), the operating frequency, and the total force applied by the compactor increased, and (c) D_r decreased as the towing speed increased.
3. A statistical relationship exists between D_r and the dimensionless factor α. This reflects some of the important properties of the soil, vibratory compactor, and compaction procedure. This relationship is given by the equation, $D_r = 50\ \alpha^{0.07}$.

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