Ultimate bearing capacity of shallow foundations on sand with geogrid reinforcement

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Ultimate bearing capacity of shallow foundations on sand with geogrid reinforcement

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Laboratory model test results for the ultimate bearing capacity of strip and square foundations supported by sand reinforced with geogrid layers have been presented. Based on the model test results, the critical depth of reinforcement and the dimensions of the geogrid layers for mobilizing the maximum bearing-capacity ratio have been determined and compared.

Key words: bearing capacity, geogrid, model test, reinforced sand, shallow foundation.

Des résultats d'essais sur modèle en laboratoire pour déterminer la capacité portante ultime de fondations filantes ou carrées reposant sur du sable armé de couches de géogrille ont été présentés. Sur la base des résultats d'essais sur modèle, la profondeur critique de l'armature et les dimensions des couches de géogrille pour mobiliser le rapport maximum de capacité portante ont été déterminées et comparées.

Mots clés : capacité portante, géogrille, essai sur modèle, sable armé, fondation superficielle.

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Introduction

During the last 15 years, several papers have been published as related to the beneficial effects of soil reinforcement on the ultimate bearing capacity of shallow foundations. The results of most of these studies reported so far in the literature are based on laboratory model tests. The reinforcing materials used for these studies have been metal strips (Binquet and Lee 1975; Fragaszy and Lawton 1984; Huang and Tatsuoka 1988, 1990), rope fibers (Akinmusuru and Akinbolande 1981), metal bars (Huang and Tatsuoka 1990), geotextiles (Guido et al. 1985), and geogrids (Guido et al. 1986). All of the laboratory model test results with geosynthetic reinforcement available at this time have been conducted with square foundations. The purpose of this note is to present and compare the results of some recent laboratory model tests on square and strip foundations supported by sand reinforced by layers of geogrid.

Bearing-capacity ratio

Figures 1*a* and 1*b* show a strip (width B) and a square ($B \times B$) foundation being supported by sand which is reinforced with N number of geogrid layers. The vertical spacing between consecutive geogrid layers is h. The top layer of geogrid is located at a depth u measured from the bottom of the foundation. The width of the geogrid layers under the strip foundation is b, and those under the square foundation measure $b \times b$. The depth d of reinforcement below the bottom of each foundation is

$$[1] \quad d = u + (N - 1)h$$

For surface foundations on dry sand without reinforcement, the ultimate bearing capacity q_u can be represented by the conventional relationships (Vesic 1973) as

$$[2] \quad q_u = q_{u(st)} = 0.5\gamma_d B N_\gamma$$

and

$$[3] \quad q_u = q_{u(sq)} = 0.3\gamma_d B N_\gamma$$

where $q_{u(sq)}$ and $q_{u(st)}$ are the ultimate bearing capacities of square and strip foundations, respectively; γ_d is the unit dry weight of soil; and N_γ is the bearing-capacity factor.

When the sand is reinforced with geogrid layers, the ultimate bearing capacity $q_{u(R)}$ of each foundation will increase. The increase in the ultimate bearing capacity can be expressed in a nondimensional form called the bearing-capacity ratio BCR.

$$[3] \quad \mathrm{BCR} = \frac{q_{u(R)}}{q_u}$$

For similar soil, geogrid, and h/B, the magnitude of the bearing-capacity ratio for a given foundation will depend on (*i*) d/B, (*ii*) b/B, and (*iii*) u/B. However, each of the above three parameters will have a critical value (i.e., $d/B = (d/B)_{cr}$, $b/B = (b/B)_{cr}$, and $u/B = (u/B)_{cr}$) beyond which further increase will not have any significant influence on the bearing-capacity ratio. The major purpose of this study is to evaluate and compare $(d/B)_{cr}$, $(b/B)_{cr}$ for square and strip foundations.

Laboratory model tests

The model square foundation used for this study measured 76.2 × 76.2 mm. The strip foundation had a width of 76.2 mm and a length of 304.8 mm. They were made out of aluminum plates. Rough bottom condition of the model foundations was achieved by cementing a thin layer of sand using glue. Bearing-capacity tests on the strip foundation was conducted in a box measuring 1.1 m (length) × 304.8 mm (width) × 914 mm (depth). The inside walls of the box and the edges of the model foundation were polished as much as possible to reduce fric-

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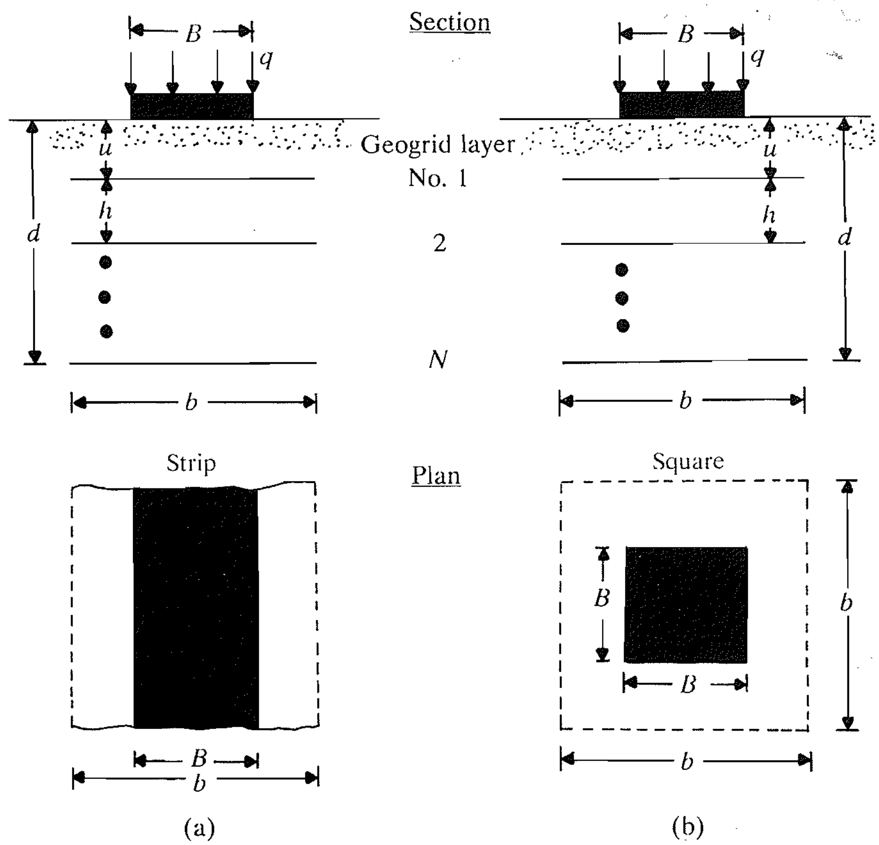

FIG. 1. Square and strip foundations supported by sand reinforced with layers of geogrid. q, load per unit area.

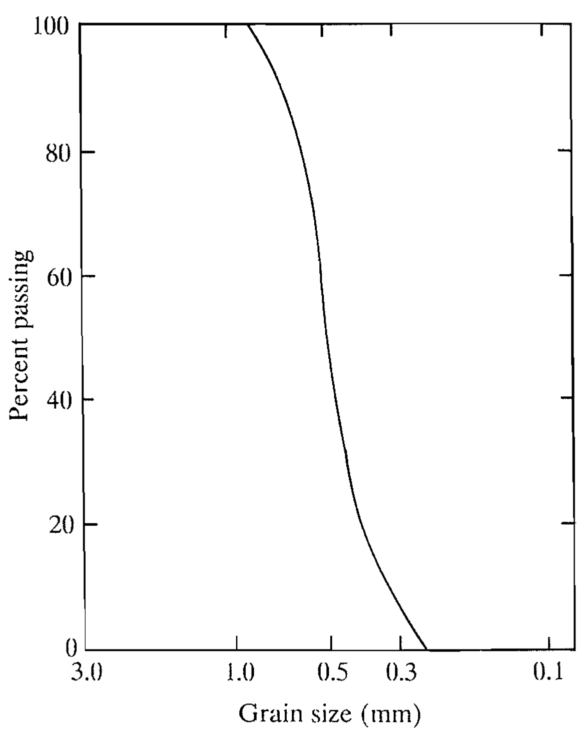

FIG. 2. Grain-size distribution of sand used for model tests.

tion. Tests on the square foundation were conducted in another box having dimensions of 760 × 760 × 760 mm. The sides of both of the boxes were heavily braced to avoid lateral yielding.

A fine, rounded silica sand was used for the present model tests. The grain-size distribution curve of the sand is shown in Fig. 2. For all tests, the average unit weight γ_d and the relative density of compaction of sand were kept at 17.14 kN/m^3 and 70%, respectively. The range of variation of the unit weight of compaction was ±6% of the average value. The average peak friction angle ϕ of this sand at the test conditions as determined from direct shear tests was 41° (with a range of 39.5–42°). A biaxial geogrid was used for the present tests (Tensar BX1000(SSO)). The physical properties of the geogrid are given in Table 1.

TABLE 1. Physical properties of the geogrid

Item	Property
Structure	Punched sheet drawn
Polymer	Polypropylene – high-density polyethylene copolymer
Junction method	Unitized
Aperture size (machine direction; cross machine direction)	25.4 mm; 33.02 mm
Nominal rib thickness	0.762 mm
Nominal junction thickness	2.286 mm

In conducting a model test, sand was poured into the test box in 25.4-mm-thick layers using a raining technique. The accuracy of sand placement and the consistency of placement density were checked by placing small cans with known volumes at different locations in the box. Geogrid layers were placed in the sand at desired values of u/B and h/B. The model foundation was placed on the surface of the sand bed. Load to the model

TABLE 2. Details of model tests

Test series	Details
A	Tests on unreinforced sand
B	Variable parameter: N (i.e., d/B) Constant parameters: $u/B = h/B = 1/3$; $b/B = 10$ (for strip) and 6 (for square)
C	Variable parameter: b/B Constant parameters: $u/B = h/B = 1/3$; $N = 6$ (for strip) and 4 (for square)
D	Variable parameter: u/B Constant parameters: $h/B = 1/3$; $N = 6$ (for strip) and 4 (for square); $b/B = 8$ (for strip) and 4 (for square)

foundation was applied by a hydraulic jack. Rotation of the foundation during load application was allowed. The load and the corresponding settlement s along the center line were measured by a proving ring and two dial gauges. Details of the tests conducted under this program are given in Table 2. The ultimate load for each model test was determined by using the criteria described by Vesic (1973), which is the peak load obtained from the load–displacement diagram of each test.

Model test results

Test series A

These tests were conducted on unreinforced sand. Based on the load q per unit area versus settlement s plots obtained from the bearing-capacity tests conducted on the model strip and square foundations, the experimental ultimate bearing capacities were determined to be 83 and 63 kN/m^2, respectively. The theoretical values of q_u were calculated by using [2] and [3] and the bearing-capacity factors provided by Vesic (1973) for peak friction angle $\phi = 41°$ (i.e., $N_\gamma = 130.22$). These values were obtained as $q_{u(st)} = 85$ kN/m^2 = 51 kN/m^2.

Test series B

Figures 3 and 4 show the nature of experimental q versus s plots obtained from tests with strip and square foundations. From these figures it appears that, for a given foundation, the magnitude of $q_{u(R)}$ increases with N along with an increase of the settlement at ultimate load. It needs to be pointed out, however, that for similar values of q the settlement on reinforced soil was lower than that on unreinforced soil. For tests with a strip foundation, the settlement at ultimate load (Fig. 3) almost doubled when N was increased from 1 to 3. For $N \geq 3$, the settlement at ultimate load remained practically constant. However, this was not the case for the square foundation.

Figure 5 shows plots of the variation of BCR with d/B obtained by using the ultimate bearing capacity values from tests series A and Figs. 3 and 4. For a given foundation the magnitude of the BCR increases with d/B up to an approximate maximum value and remains practically constant thereafter. The critical value of d/B (= $(d/B)_{cr}$) is about 2 for strip foundations and 1.4 for square foundations. Guido et al. (1986) determined $(d/B)_{cr}$ for square foundations to be 1–1.25. Hence, as the

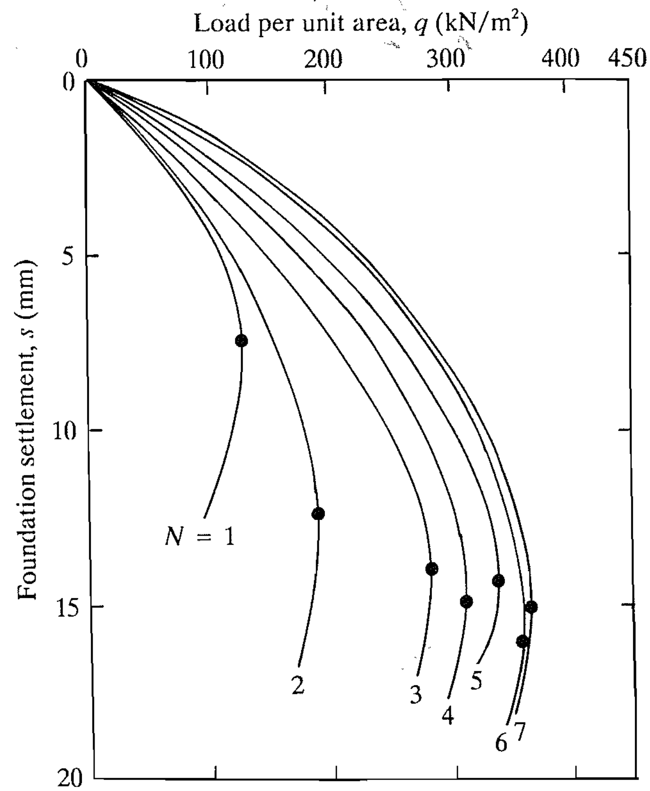

FIG. 3. Plot load per unit area vs. settlement for strip foundations (test series B). ●, ultimate bearing capacity $q_{u(R)}$. $u/B = h/B = 0.333$; $b/B = 10$.

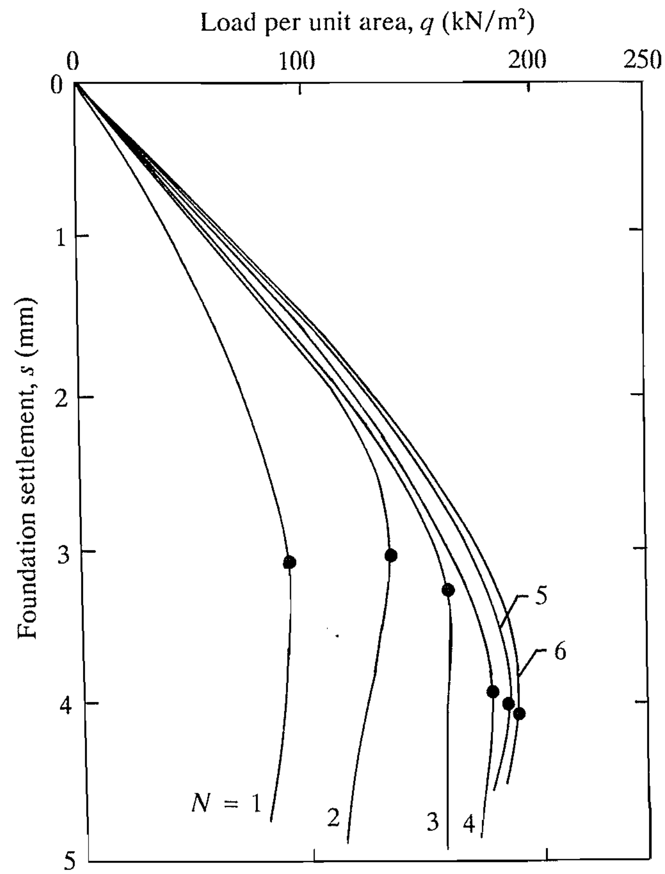

FIG. 4. Plot load per unit area vs. settlement for square foundations (test series B). ●, ultimate bearing capacity $q_{u(R)}$. $u/B = h/B = 0.333$; $b/B = 6$.

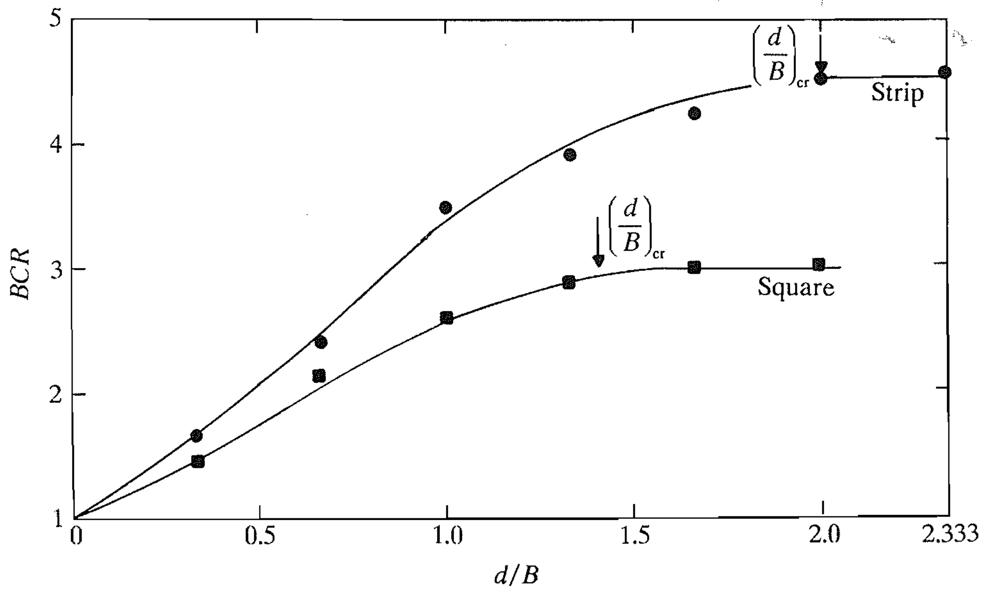

FIG. 5. Variation of bearing-capacity ratio BCR with d/B (test series B). $u/B = h/B = 0.333$; $b/B = 10$ (for strip) and 6 (for square).

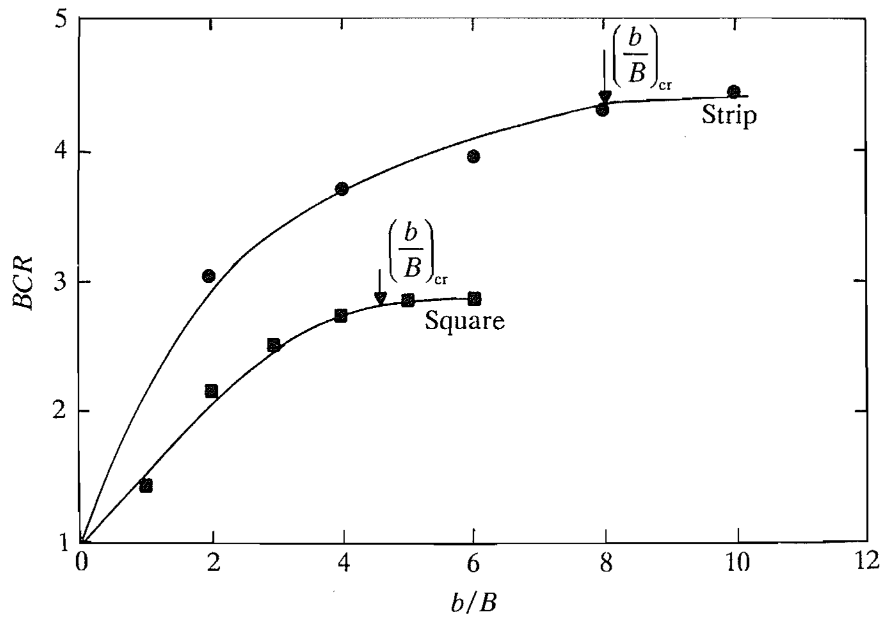

FIG. 6. Variation of bearing-capacity ratio BCR with b/B (test series C). $u/B = h/B = 0.333$; $N = 6$ (for strip) and 4 (for square).

B/L (L = length of foundation) ratio of the foundation decreases, the magnitude of $(d/B)_{cr}$ increases from about 1.4 to about 2.

Test series C

The tests in this series were conducted to determine the optimum dimension $(b/B)_{cr}$ of the reinforcing geogrid layers. The depths of the reinforcement were kept at about the same level as $(d/B)_{cr}$ determined from test series B.

The bearing-capacity ratios obtained from these tests have been plotted with b/B in Fig. 6. It can be seen from this figure that the BCR attains a maximum at a $(b/B)_{cr}$ of 8 for strip foundations and about 4.5 for square foundations. Hence the optimum reinforcement width $(b/B)_{cr}$ increases with the decrease of the B/L ratio of the foundation. In the study of Guido et al. (1986), the magnitude of $(b/B)_{cr}$ for square foundations was determined to be about 2.5–3.

Test series D

Binquet and Lee (1975) observed that, to obtain maximum benefit from the reinforcement, it is desirable that u/B be less than about 0.67. For larger u/B ratios, the failure surface in soil at ultimate load will be fully located above the top layer of reinforcement, and the top layer will act as a semirigid surface. In their bearing-capacity tests with a square foundation supported by sand with geogrid reinforcement, Guido et al. (1986) determined u/B to be approximately 0.75. To verify this fact, the present tests in series D were conducted with u/B as the variable parameter. The results obtained from

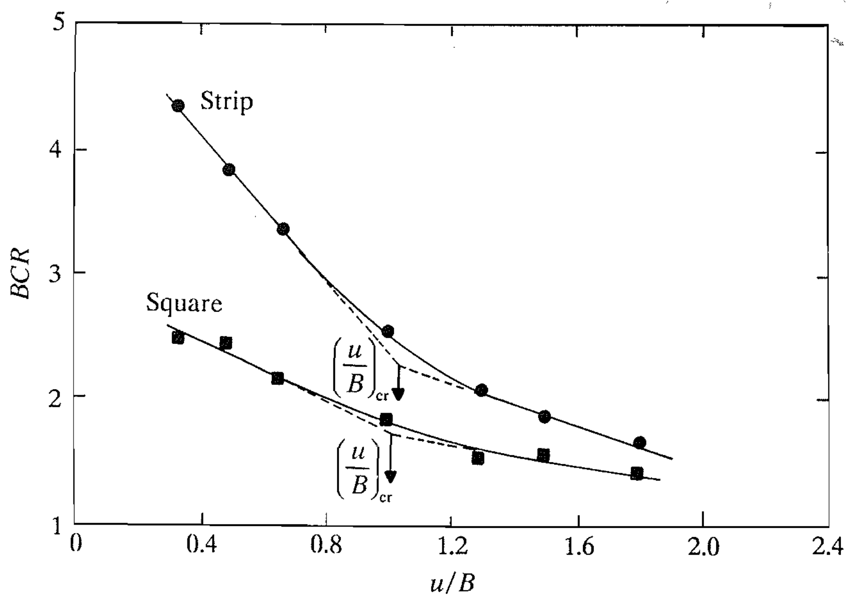

FIG. 7. Variation of bearing-capacity ratio BCR with u/B (test series D). h/B = 0.333; b/B = 8 (for strip) and 4 (for square); N = 6 (for strip) and 4 (for square).

these tests have been plotted in Fig. 7. It shows that, for a given foundation, the magnitude of the BCR decreases with the increase of u/B. The magnitude of $(u/B)_{cr}$ can be determined by drawing tangents to the initial and end portions of the BCR versus u/B curves. The point of intersection of these two tangents may be defined as $(u/B)_{cr}$. For the present test results, $(u/B)_{cr}$ is about 1 for square and strip foundations. For $u/B > (u/B)_{cr}$, the BCR versus u/B plots when extended give a BCR $\approx$ 1 at $u/B \approx$ 2.5. Laboratory model tests on foundations supported by sand with a rigid rough base at a limited depth have shown similar results (Pfeifle and Das 1979).

Conclusions

Laboratory model test results for the ultimate bearing capacity of strip and square foundations supported by sand with geogrid reinforcement have been presented. Based on the model test results, the following conclusions can be drawn.

(1) For development of maximum bearing capacity, the effective depth of reinforcement is about $2B$ for strip foundations and $1.4B$ for square foundations.

(2) Maximum width of reinforcement layers required for mobilization of maximum bearing-capacity ratio is about $8B$ for strip foundations and $4.5B$ for square foundations.

(3) The maximum depth of placement of the first layer of geogrid should be less than about B to take advantage of reinforcement.

(4) The influence of foundation size and scale effects has not been investigated. Consequently, these findings cannot be directly transported to full-size foundations without additional verification.

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