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Behavior of Shallow Strip Anchors in Sand: A Finite Element Study

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Abstract: A finite element analysis of the behavior of shallow strip anchors in sand was performed. The analysis was carried out on rigid strip anchors that are embedded in loose, medium dense and dense sands. The results showed that the failure mode of strip shallow anchors is typical of rigid body movement of the soil comprised between the anchor plate and the ground surface. At ultimate load, the region between the anchor plate and the ground surface reaches plasticity by Mohr-Coulomb's yield criterion while the small region below the plate is under tension cut-off. The analysis of the anchor capacity using the pullout factor, a dimensionless parameter, showed that the pullout factor is constant for values of the depth ratio H/B less than 5 and increases for larger values. The range of the depth ratios where the failure mode is typical of rigid body movement of the soil lying above the anchor is rather small. For larger values of depth ratio the plastic zone in the sand expands below the anchor and starts spreading widely on the ground surface.

Key words: *Ground anchor, Sand, Soil behavior Finite element analysis, Plane strain problem, Rigid body,*

INTRODUCTION

Ground anchors are used for anchoring structures that transmit considerable tensile forces to their foundations. Examples of such structures are high-mast transmission towers, suspended or arch bridges, offshore structures, structures supporting excavations, dams, sheet pile walls, etc… as shown in Figure 1.

Anchors have different shapes (piles, blocks, marine anchors, plates, …) and can be made of a variety of materials. Depending on the type and size of the structure to be anchored, anchors may be embedded at shallow or deep depth.

A plate anchor consists of a plate, usually made of metal or concrete, connected to the anchored structure by means of a tie rod or a cable. With respect to Figure 2, we consider anchor plates of width B and length L buried at depth H in sand. The soil properties are the Young's modulus of elasticity E, Poisson's ratio ν, the angle of internal friction ϕ, the relative density D_r and the unit weight γ.

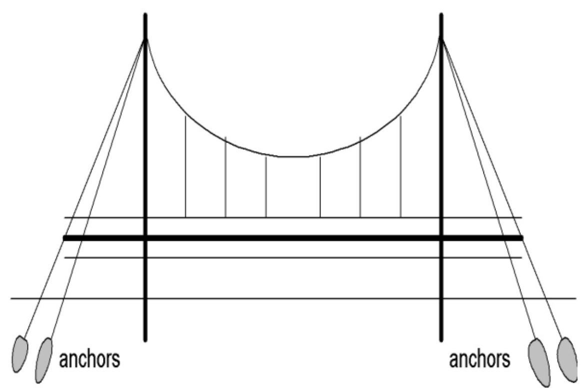

Figure 1 Example of anchored structure

In the present study, a rigid strip anchor plate was considered. The load is applied by the anchor plate to the surrounding soil. The behavior of the sandy soil around the anchor plate is discussed. Parameters influencing the anchor capacity are also discussed.

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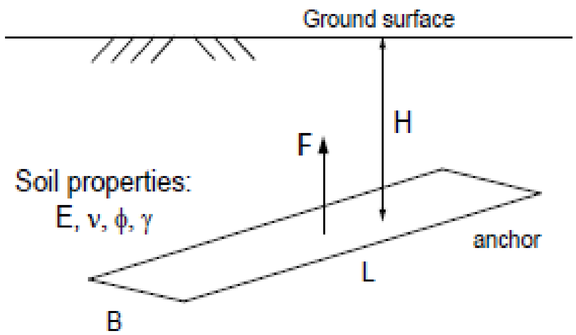


Figure 2 Soil-anchor model

BACKGROUND

Several linear analytical techniques to study the elastic behaviour of soils under anchor loading have been reported by (Fox [1], Rowe and Booker [2], Selvadurai [3]. However, the behaviour of soil in general and that of sand in particular is not elastic, and such methods cannot give reliable results, even at working loads. Later in 2004, Merouani and Davies considered the initiation of yield in a Mohr-Coulomb material loaded by a rigid plate [4].

More powerful methods such as the finite element method have also been used as early as 1982 by Rowe and Davis [5,6], Ito and Kitahara [7], Desai et al [8] and many others. The major difficulties in their use arise from the determination of appropriate stress-strain relations for sand. Merifield et al [9,10] used a finite element formulation of the lower bound theorem of limit analysis for plate anchors in sand and in clay. More recently, Yang and Yu [11] used the so-called non-coaxial as well as the conventional elastic-perfectly-plastic Drucker-Prager model for the finite element analysis of anchor plates buried in cohesionless soils. The results obtained from non-coaxial and coaxial models gave the same uplift capacity.

FINITE ELEMENT ANALYSIS

The behaviour of shallow and deep anchors as well as horizontal and vertical anchors was investigated by many authors. In this paper the behaviour of strip anchors embedded at shallow depth in sand was analysed through a plane strain problem of anchors by the finite element method.

PLAXIS, a widely commercialised finite element program for geotechnical applications was used for the analysis of plate anchors embedded in sand.

In order to investigate the behaviour of shallow horizontal anchors in sand examples of strip anchor embedded in sand was ran using Plaxis. The stress distribution, the displacement field and the plastic soil zone around the anchor were shown for shallow horizontal anchors loaded vertically. The anchor plate was considered to be rigid and this was modelled as prescribed displacements as shown in Figure 3.

Plane strain problem for the general behaviour of shallow strip anchors buried in sand was modelled and ran. A rectangular plate, long enough to be considered as strip plate (L>>B) was buried in a sand mass. The strip plate was buried horizontally at shallow depths. The embedment ratios were considered in the shallow range H/B=2 to 6.

Simulations were performed in sand at three different densities. The values of the sand parameters represent a loose sand, a medium dense sand and a dense to very dense sand. Table 1 summarises the properties of the three sands used in the analysis. The angle of dilatancy ψ was considered to be zero in all three sand models.

Table 1 Sand properties used in FEM analysis

Loose sand	Medium dense sand	Dense sand
γ=16 kN/m^3 E=10 MPa ν=0.20 G=4.17 MPa E_{oed}=11.1 MPa ϕ=30° ψ=0	γ=16.5 kN/m^3 E=12.5 MPa ν=0.25 G=5.0 MPa E_{oed}=15.0 MPa ϕ=35° ψ=0	γ=17 kN/m^3 E=15 MPa ν=0.30 G=5.77 MPa E_{oed}=20.2 MPa ϕ=40° ψ=0

The initial stress was calculated based on Jaky's equation that means that the coefficient of earth pressure at rest was taken as:

$$K_o = 1 - \sin\phi$$

A strip plate is embedded horizontally in a mass of sand at depth ratios H/B=2 ; 4 ; 5 and 6.

Figures 3 shows a plate anchor buried at depth ratio H/B=4 (H=1.60 m and having a width B=0.40 m). The plate is loaded vertically. Boundary conditions are smooth on the sides.

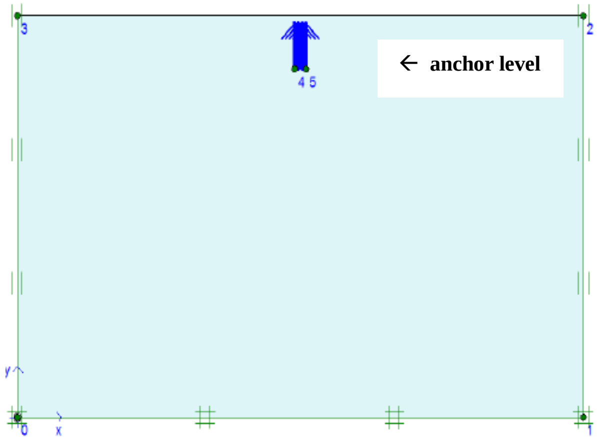


Figure 3 FE model of shallow horizontal strip anchor buried in sand at H/B=4

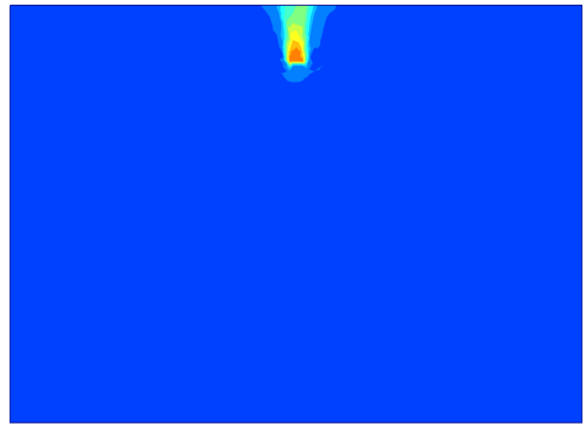


Figure 4b Total displacements for horizontal shallow strip anchor in sand at H/B=4

RESULTS

The results from the finite element analysis are shown in Figures 4 to 9. Figures 4 to 7 show various components of stress as well as the displacements in a sand mass that is loaded by a rigid intrusion at embedment depth ratio H/B= 4.

Figures 4a and 4b show the total displacements due to a horizontal strip anchor loaded by a vertical force. It shows that points located between the anchor plate and the soil surface are lifted up while the rest of the sand mass is not moved. The figure shows a rigid body movement of the sand between the anchor plate and the ground surface.

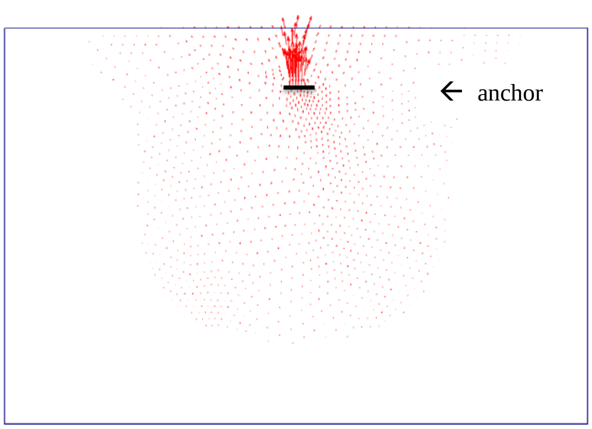


Figure 4a Total displacements for horizontal shallow strip anchor in sand at H/B=4

Figures 5 and 6 show the normal vertical stress distribution and the normal horizontal stress distribution in a sand mass loaded by a shallow horizontal strip anchor. It is the region of soil close to the anchor plate that is most affected by the load. Points remote from the anchor do not seem to be greatly affected by the load induced by the rigid intrusion.

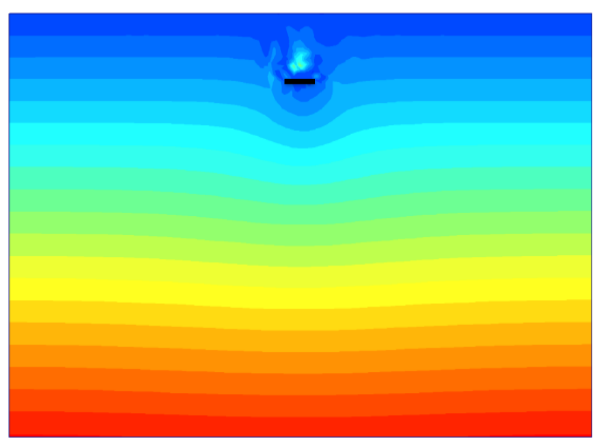


Figure 5 Normal vertical stress σ_y for horizontal shallow strip anchor in sand at H/B=4

The normal horizontal stress distribution represented in Figure 6 does not show large variations as the normal vertical stress does. It shows small variations of the normal stress with a relief of the stress in the zone below the anchor plate, quite similarly to the vertical normal stress. This was expected as the plate anchor is loaded vertically.

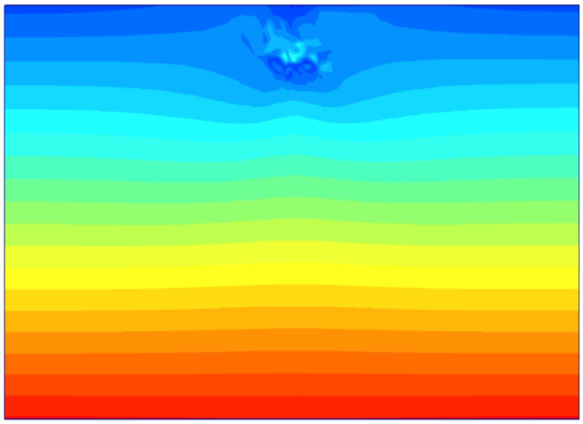


Figure 6 Normal horizontal stress σ_x for horizontal shallow strip anchor in sand at H/B=4

The shear stress τ_{xy} is maximum at the edges of the anchor plate along the shear planes that are formed between the solid block consisting of the anchor plate and the soil above it, on the one hand and the remaining sand.

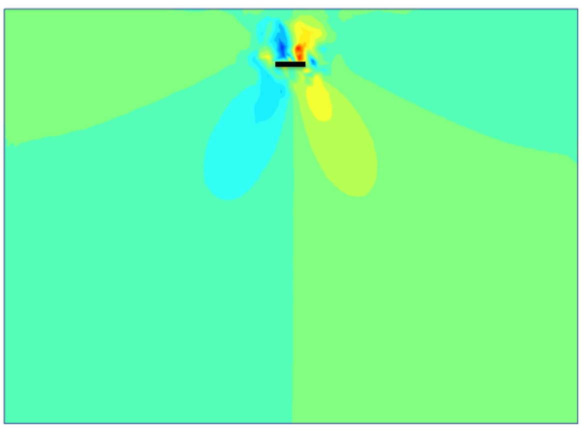


Figure 7 Shear stress τ_{xy} for horizontal shallow strip anchor in sand at H/B=4

Figure 7 shows the points that yielded under Mohr-Coulomb yield criterion for a horizontal shallow strip plate (small red squares in red). This yield criterion is expressed below as:

$$\tau = c + \sigma \tan\phi$$

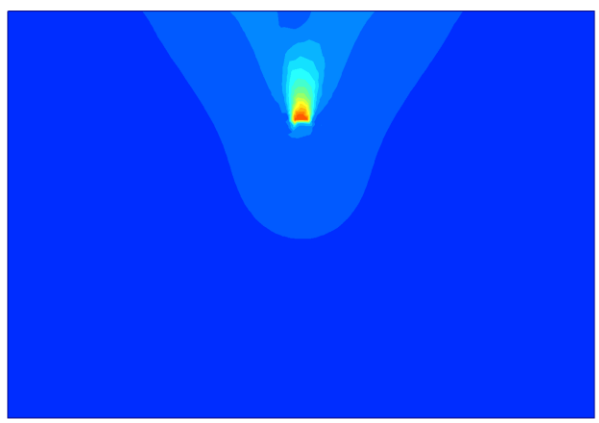
These plastic points appeared essentially around the anchor and then expanded upwards. In the region between the anchor plate and the soil surface most of the points yielded. Tension cut-off occurred in the region below the plate and at the soil surface below the anchor (points in black).

Figure 8 Plastic points for horizontal shallow strip anchor in sand at H/B=4

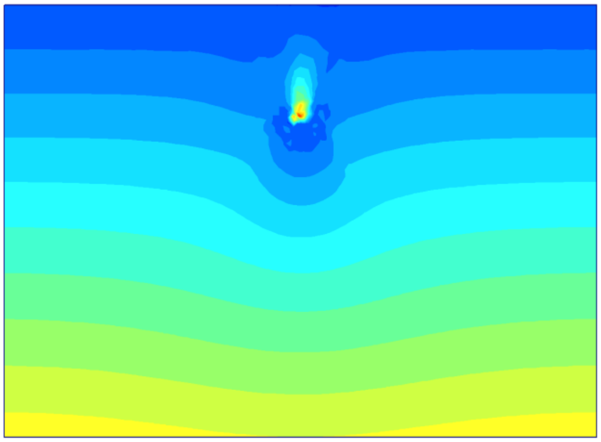
Figures 9 (a, b, c, d and e) show the total displacement of the sand around the anchor, the vertical stress, the horizontal stress, the shear stress and the plastic points for an anchor plate buried at H/B=6. The magnitude of the sand displacement at the ground surface is decreased. The sand in the vicinity of the anchor plate is moved due to the action of the uplift force while points remote undergo smaller displacements. There is no clear rigid body movement.

The general shape of the normal and shear stress components is similar for plates anchored at H/B=4 and H/B=6, however their magnitudes are larger as larger forces are involved.

Also the plastic zone expands more when the embedment depth increases.



(a)



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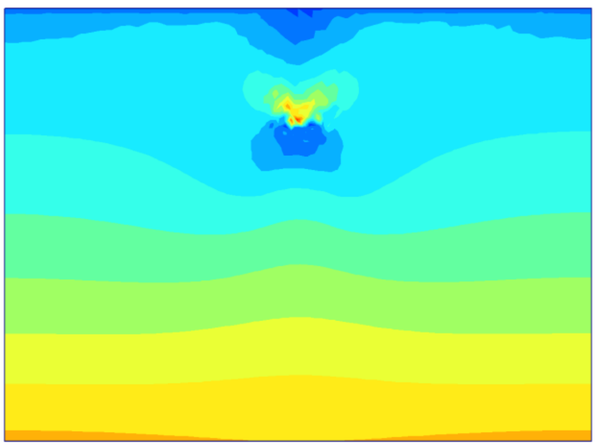

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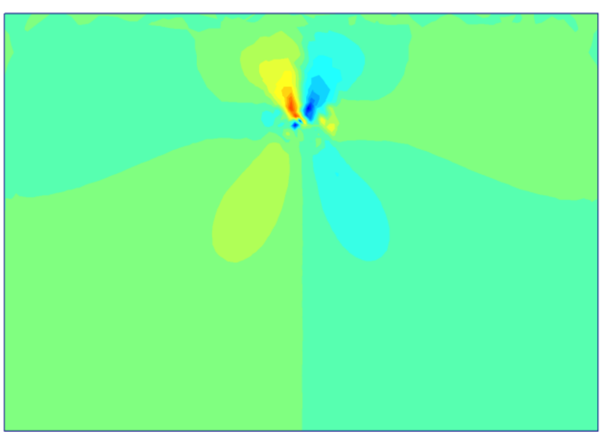
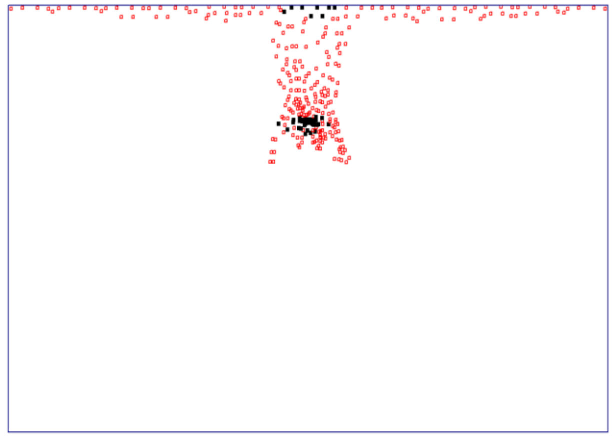


(d)



(e)

Figure 9 (a) Total displacements, (b) Normal vertical stress σ_y (c) Normal horizontal stress σ_x (d) Shear stress τ_{xy} and (e) Plastic points for horizontal strip anchor in sand at H/B=8

Figures 10 and 11 show the capacity of the anchor as function of the anchor displacement and the depth ratio, respectively.

Figure 10 shows the load-displacement response of shallow horizontal strip anchors buried in sand for different depth ratios using the finite element analysis. It shows that strip anchors at larger depth ratios require larger displacements to reach the ultimate state. Also, the ultimate uplift force increases with increasing depth ratio. This is considered for depth ratios in the range of shallow anchor values.

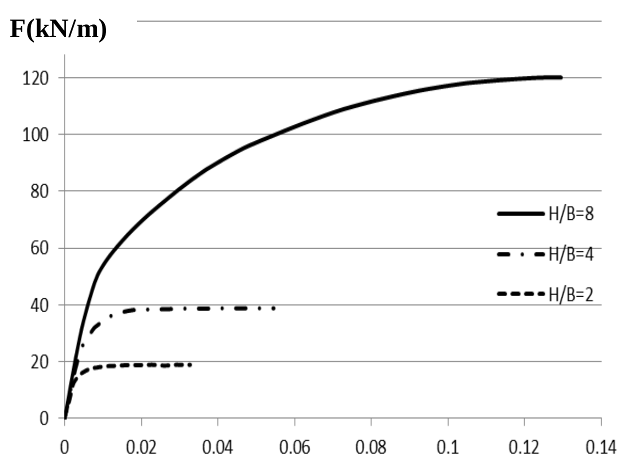


Figure 10 Vertical uplift force F [kN/m] versus anchor displacement δ [m] for various depth ratios

For the analysis of the anchor capacity at shallow depths, a dimensionless parameter is considered. The dimensionless parameter for the anchor capacity is the pullout factor Nu that is defined as follows:

$$N_U = \frac{F_U}{BLH\gamma}$$

where;

F_u is the ultimate pullout force,

B, L are anchor width and length, respectively

H is embedment depth, and

γ is sand unit weight

Figure 11 shows the pullout factor Nu as function of the depth ratio H/B. These two dimensionless parameters may express the anchor capacity as function of the depth. The variation of the anchor capacity is also analyzed for sands with different angles of internal friction.

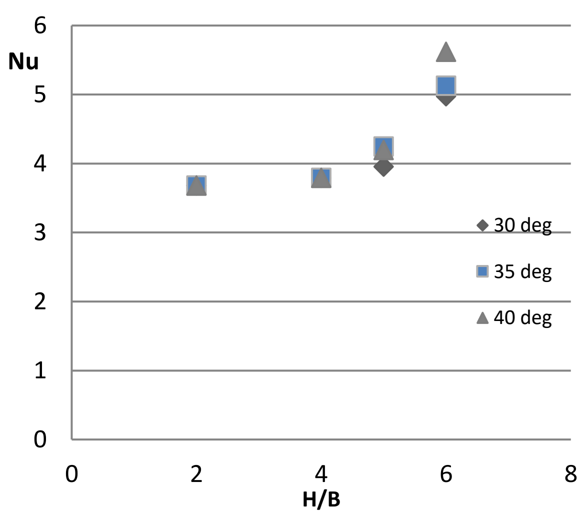


Figure 11 Pullout factor Nu versus depth ratio H/B

The results show that the anchor pullout factor slightly changed for values of embedment ratio up to 4. However, for values of the depth ratio larger than 4 Nu starts to increase. This means that the anchor behavior changes from the general trend of shallow anchors that is shown for depth ratios less than 5 to a trend of transition before reaching the range of depth ratios typical of deep anchors.

However, the influence of the angle of internal friction seems to be very small. This point needs to be further investigated. The uplift capacity of anchor plates in sands is expected to be more sensitive to the angle of internal friction.

The behaviour of shallow strip anchors in sand as shown in the present finite element study is similar to the experimental work performed by the authors and that is shown in the photo below. Photo 1 shows a rigid body movement provoked by the uplift of the plate anchor. This behaviour was also mentioned by Balla [12], Meyerhof and Adams [13], Das and Seeley [14] and other authors for anchors embedded at shallow depths.

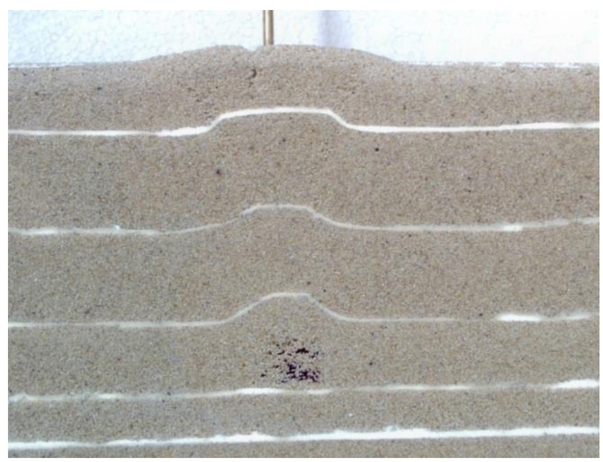


Photo 1 Sand displacement due to horizontal strip anchor uplift

CONCLUSION

A simple suggestion for the determination of the anchor capacity for shallow strip anchor plates is proposed for the range of depth ratios less than 5. The anchor capacity can be expressed as function of the anchor dimensions, the depth of embedment and the soil unit weight.

The proposed expression of the anchor capacity buried in sand for the range of shallow depths is:

$$N_U = 3.8$$

or

$$P_U = 3.8HBL\gamma$$

for H/B < 5

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