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Experimental And Numerical Investigations On Uplift Behaviour Of Plate Anchors In Cohesionless Soil

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ABSTRACT

In this study, series of small scale laboratory pull-out tests were conducted on anchors embedded in sand. Model tests were performed in a test box. The effects of embedment ratio of anchor plates and relative density of sand on uplift capacity behaviour were investigated. Also numerical analyses of the test models were carried out using the finite element package Plaxis. Based on the results, it can be concluded that the embedment ratio of anchor plates and relative density of sand are main parameters that affect the uplift capacity of anchor plates. At the end of the study, the results of experimental study were also compared with the results of numerical solutions.

Keywords: *Anchor plates, Embedment ratio, Finite element methods, Uplift capacity.*

INTRODUCTION

Anchors are used to support structures such as transmission towers, anchored bulkheads, submerged pipelines, and tunnels. Research into the uplift resistance of an anchor provides a useful analogue for a soil interaction problem. Various studies of anchors have been conducted by numerous researchers. The uplift resistance of anchors in sand has been evaluated in various studies using experiments and analyses [1]. These studies have focused on the estimation of the vertical uplift resistance of an anchor buried horizontally in homogeneous ground. Additionally, theoretical studies of anchors have focused on a rigid plastic analysis [2,3]. One downside to this approach is the introduction of ad hoc assumptions regarding the shape of failure surface observed during the test, and does not consider progressive failure. Rowe and Davis [4] studied the behavior of an anchor plate in sand using elastoplastic finite-element analysis based on the Mohr–Coulomb failure criterion. Sutherland [5] stated that the finite-element analysis for cohesionless soils shows unsatisfactory results. Previous studies of elastoplastic finite-element analysis have not fully considered the progressive failure [6,7]. Research into anchors has shown that two main categories can be identified: a shallow anchor and a deep anchor [8,9]. For the case of shallow anchors, the failure surface in soil mass extends from the anchor to the soil surface. Sakai and Tanaka [10] studied the uplift resistance of a shallow anchor in dense sand using elastoplastic finite-element analysis. In their analysis, progressive failure with shear band effect was introduced into the constitutive equation. The result of this analysis was close to the experimental data, and the scale effect due to the progressive failure was evaluated.

PREVIOUS STUDIES

During the last fifty years, several theoretical and semi-empirical methods have been developed to predict the net ultimate uplifting load of continuous, circular and rectangular foundations embedded in sand. The ultimate uplift capacity of the foundation is the sum of two components: (a) the weight of the soil and the foundation in the failure zone and (b) the shearing resistance developed along the failure surface. Based on results of several model and field tests conducted in dense soil, Balla [11] established that, for shallow circular foundation, the failure surface in soil make an angle and the angle α is equal to 45-ϕ/2 as shown Figure 1. Existing literature, in general, Balla's theory is in good agreement with the uplift capacity of shallow foundations embedded in dense sand at an embedment ratio of Df/B≤5. However for foundations located in loose and medium sand, the theory overestimates the ultimate uplift capacity. The main reason Balla's theory overestimates the ultimate uplift capacity for Df/B> about 5 even in dense sand because it is essentially deep foundation condition, and the failure surface does not extend to the ground surface.

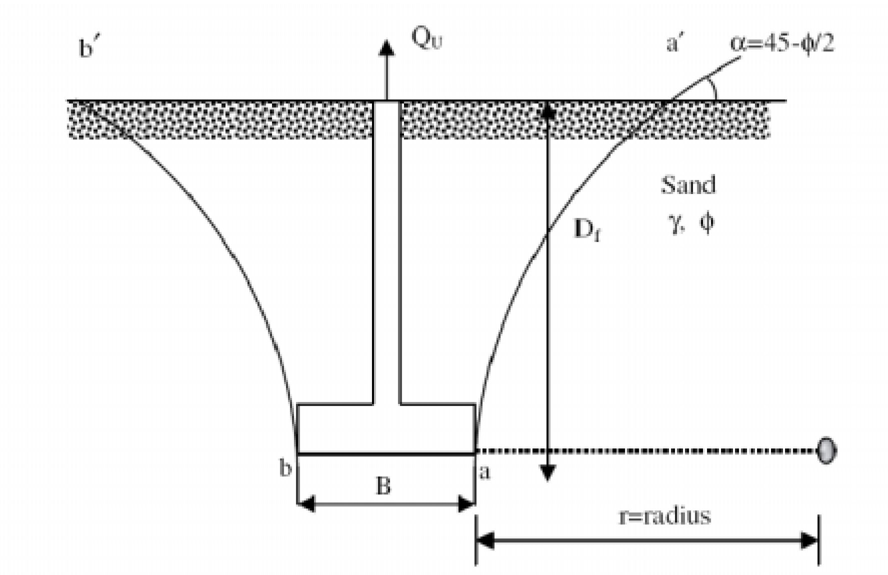

Figure 1. Balla's theory for shallow circular foundations [12]

Baker and Kondner [8] confirmed Balla's major findings regarding the behavioural difference of deep and shallow anchors in dense sand. Sutherland [13] presented results for the pull-out of 150mm horizontal anchors in loose and dense sand, as well as large diameter shafts in medium dense to dense sands. It was concluded that the mode of failure varied with sand density and that Balla's analytical approach may give reasonable results only in sands of intermediate density. Kananyan [14] presented results for horizontal circular plate anchors in loose to medium dense sand. He also performed a series of tests on inclined anchors and observed the failure surface, concluding that most of the soil particles above the anchor moved predominantly in a vertical direction. In these tests, the ultimate capacity increased with the inclination angle of the anchors. One of the most rational methods for estimating the ultimate uplift capacity of a shallow foundation was proposed by Meyerhof and Adams [15]. At ultimate load the failure surface in soil makes an angle α with the horizontal. The magnitude of α depends on several factors, such as the relative density of compaction and the angle of friction of the soil, and it varies between 900-ϕ/3 to 900-2ϕ/3. Vesic [16] studied the problem of an explosive point charge expanding a spherical cavity close to surface of a semiinfinite, homogeneous, isotropic solid. For Vesic study, summing the components of forces in the vertical direction can determine the ultimate pressure p_o in the cavity.

Extensive chamber testing programs have been performed by Murray and Geddes [2,17] performed pull-out tests on horizontal strip, circular, and rectangular anchors in dense and medium dense sand with 43.6° and 36° respectively. Anchors were typically 50.8mm in width/diameter and were tested at aspect ratios (L/B) of 1, 2, 5 and 10. Based on their observations, Murray and Geddes made several conclusions: (1) the uplift capacity of rectangular anchors in very dense sand increases with embedment ratio and with decreasing aspect ratio L/B ; (2) there is a significant difference between the capacity of horizontal anchors with rough surfaces compared to those with polished smooth surfaces (as much as 15%); (3) experimental results suggest that an anchor with an aspect ratio of L/B=10 behaves like a strip and does not differ much from an anchor with L/B=5, and; (4) the capacity of circular anchors in very dense sand is approximately 1.26 times the capacity of square anchors. Several of these conclusions confirm the findings of Rowe [18]. It is also of interest to note that for all the tests performed by Murray and Geddes, no critical embedment depth was observed.

More recently, Pearce [19] performed a series of laboratory pullout tests on horizontal circular plate anchors pulled vertically in dense sand. These tests were conducted in a large calibration chamber, with dimensions one meter in height and one meter in diameter. Various parameters such as anchor diameter, pullout rate and elasticity of loading system have been investigated. The model anchors used for the pullout tests varied in diameter from 50-125mm and were constructed from 8mm mild steel. Large diameter anchors were chosen (compared with previous research) due to the recognised influence of scale effects on the break-out factor for anchors of diameters less than 50mm [20].

A similar study to that of Pearce [20] was performed by Ilamparuthi et. al. [21] who conducted a series of laboratory pullout tests on horizontal circular plate anchors pulled vertically in loose to dense sand. A discussion of the observed failure mechanisms, load displacement response and critical embedment depth was also provided. A set of empirical equations were presented for estimating the break-out factors for circular anchors with any friction angle.

In this study, series of small scale laboratory pull-out tests were conducted on anchors embedded in sand. The effects of embedment ratio of anchor plates and relative density of sand on uplift capacity behaviour were investigated. The results of experimental study were also compared with the results of numerical solutions.

EXPERIMENTAL FACILITIES

Model Box

The experimental programme was performed using the facility in the Geotechnical Laboratory of the Civil Engineering Department of the Cukurova University. The apparatus used for model testing consists of a tank, a loading system and measurement system. The facility and a typical model are shown in Figure 1. Tests were conducted in a test box made of a steel frame with inside dimensions of 0.70×0.70m in plan and 0.70m in height. Two side walls of the box consist of fibreglass plate and the other sides consist of steel plate [22, 23]. Loading tests were carried out on model rigid anchors fabricated from mild steel. The model anchors were square and rectangular, with a thickness of 10mm. The load is transferred to the footing through a pulling rod as shown in Figure 1.

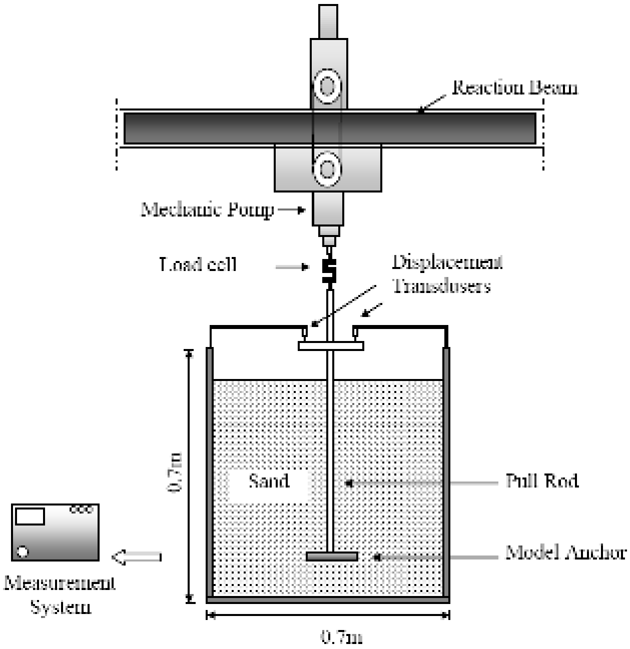

Figure 1. Test set-up and loading system

Model Ground and Model Anchors

Uniform, clean, fine sand obtained from the Çakıt River bed was used in this research. The sand was washed, dried, and sorted by particle size. The specific gravity of the soil particles was determined by the picnometer method. Three tests were carried out and the average value was obtained. The maximum and the minimum dry densities of the sand were measured. The particle size distribution was determined using the dry sieving method. Table 1 summarizes the general physical characteristics of the sand.

Table 1. Properties of sand bed

Property	**Unit**	**Value**
Coarse sand fraction	%	0.0
Medium sand fraction	%	46.40
Fine sand fraction	%	53.60
D_{10}	mm	0.18
D_{30}	mm	0.30
D_{60}	mm	0.50
Uniformity coefficient, C_u	-	2.78
Coefficient of curvature, C_c	-	1.00
Specific gravity	kN/m^3	26.8
Maximum dry unit weight	kN/m^3	17.06
Minimum dry unit weight	kN/m^3	15.03
Classification (USCS)	-	SP

The sand bed was prepared up in layers 25 mm thick. Each layer was compacted by a hand-held vibratory compactor. After the compaction of each sand layer, the next lift height was controlled using scaled lines on the glass plates of the test pit. To maintain the consistency of in-place density throughout the test pit, the same compactive effort was applied on each layer. The difference in densities measured was found to be less than 1%. The compaction technique adopted in this study provided a uniform relative density of unit weights of 15.03kN/m^3 and 17.06kN/m^3. All model anchors were fabricated from 10mm thick mild steel plate. Tests were carried out on square anchors (B=L=50mm). In the tests, the speed of the motor was adjusted to give anchor displacement rate of 0.96mm/min. The pullout displacement was transmitted to model anchor through the pulling rod, connected to loading arrangement.

TEST RESULTS

Test Variables

The main parameters investigated in the test program are the effects of embedment ratio of anchor plates, and relative density of sand on uplift capacity. The embedment ratios of the anchor were varied from 1 to 8 in the tests.

The Effects of Relative Density and Embedment Ratio

In this study, the effect of the relative density of the uplift capacity of different embedment ratio were investigated. The results are expressed in terms of break out factor (Fq) and breakout factor is calculated in the form $F_q=Q_u/\gamma\times A\times D_f$. Where A; area of the anchor plate, Q; uplift capacity, γ; unit weight of the sand and D_f; embedment ratio of the anchor. The uplift capacity of anchors in sand is strongly influenced by their embedment ratio and by the relative density of the sand (Figure 2). Relative density is the main parameter that affect the uplift capacity of anchor plates.

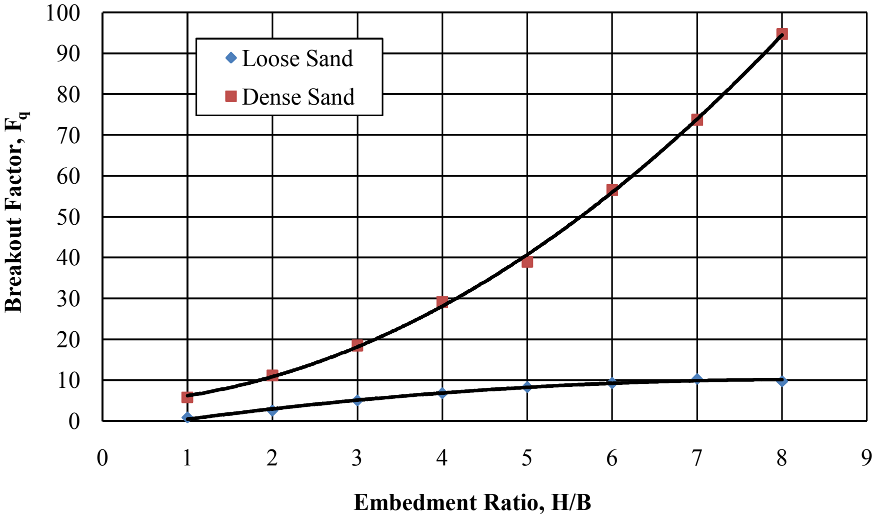

Figure 2. Effect of the relative density and embedment ratio

PLAXIS Finite Element Analyses

An elasto-plastic hyperbolic model known as the Hardening Soil Model (HSM) was selected from those available in PLAXIS to describe the non-linear sand behaviour in this study. When subjected to primary deviatoric loading, cohesionless soil shows a decreasing stiffness and simultaneously irreversible plastic strains develop. The observed relationship between the pressure and axial strain can be well approximated by a hyperbola as used in the variable elastic, hyperbolic model [24]. However the HSM is far superior to the hyperbolic model, being capable of simulating nonlinear, inelastic, stress dependent material behaviour. Limiting states of stress are described by means of the friction angle (ϕ), the cohesion (c) and the dilatancy angle (ψ). In addition the increase in soil stiffness with pressure is accounted for in all three stiffnesses used, i.e. the triaxial loading stiffness E_{50}, the triaxial unloading/reloading stiffness E_{UR} and the Oedometer loading stiffness E_{OED}. The reference stress adopted for this purpose is $100kNm^{-2}$. The initial stresses in the case of loose sand were generated using Jaky's formula which gives the at rest earth pressure coefficient $K_0=1-\sin\phi'$ where ϕ' is the friction angle in terms of effective stress [25]. Values of soil parameters used in this investigation are shown in Table 2.

Table 2: Values of soil parameters used in PLAXIS analyses

	Loose sand	Dense sand
Unit weight , γ' (kNm^{-3})	15.03	17.06
Secant stiffness, E_{50} (Nm^{-2})	20000	30000
Initial stiffness , E_{OED} (Nm^{-2})	60000	90000
Unloading/reloading stiffness, E_{UR} (Nm^{-2})	20000	30000
Cohesion ,c′ (Nm^{-2})	0.50	0.50
Friction angle ,ϕ' degrees	38	44
Dilatancy angle ,ψ degrees	8	14
Poisson's ratio ,ν	0.25	0.25
Power for stiffness stress dependency, m	0.50	0.50
At rest earth pressure coefficient, K_0	0.384	0.316

The analyses were carried out using a plane strain model for anchors in both loose and dense sand. During the generation of the mesh, 15-node triangular elements were selected in preference to the alternative 6-noded versions in order to provide greater accuracy in the determination of stresses. PLAXIS incorporates a fully automatic mesh generation procedure, in which the geometry is divided into elements of the basic element type, and compatible structural elements. The anchor was represented by a rigid beam element. Five different mesh densities are available in PLAXIS ranging from very coarse, involving approximately 75 elements in this study, to very fine, involving up to 1289 elements. In order to obtain the most suitable mesh for the present study, preliminary computations using the five available levels of global mesh coarseness for an anchor with a H/B ratio of 5 were conducted. The size and number of elements varied with anchor embedment, the mesh for an anchor at H/B=5 containing 75 elements and 667 nodal points, for example (Figure 3) . PLAXIS generates full fixity at the base of the geometry and smooth conditions at the vertical sides. Uplift loads were applied in increments of $1kNm^{-2}$. The results, compared on Figure 4 and Table 3, demonstrate a relatively minor influence of mesh coarseness. Consequently the fine mesh was adopted throughout this study.

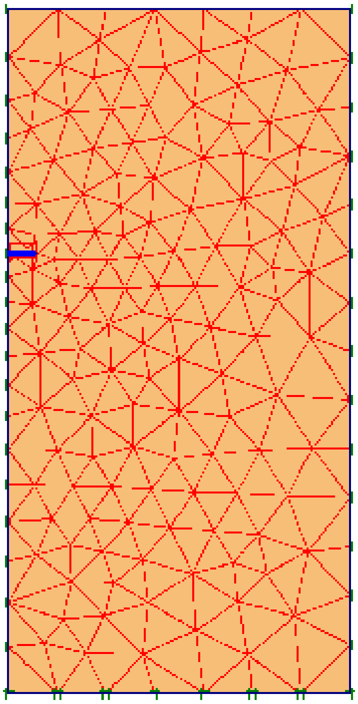

Figure 3. Meshes used in PLAXIS analyses of anchor with an embedment ratio H/B=5.

Table 3: Influence of mesh coarseness

Mesh Type	Number of Elements	Ultimate Uplift Resistance (N)
Very Coarse	75	241
Coarse	156	237
Medium	290	231
Fine	624	224
Very Fine	1289	222

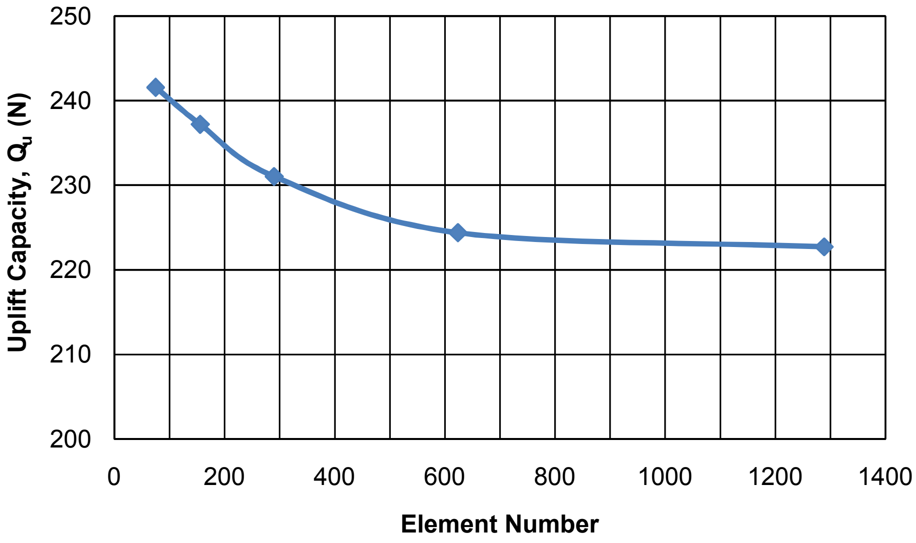

Figure 4. Influence of mesh coarseness

Comparison Between Numerical and Experimental Results

In this study, Plaxis analyses were carried out to investigate the effect of embedment ratio and relative density of sand on the uplift resistance of anchors. The results of Plaxis analyses were compared with the results of the model tests. The results are expressed and compared in terms of breakout factor. The results from the finite element analyses are in very good agreement with experimental observations in loose and dense sand (Figure 5 and 6), respectively.

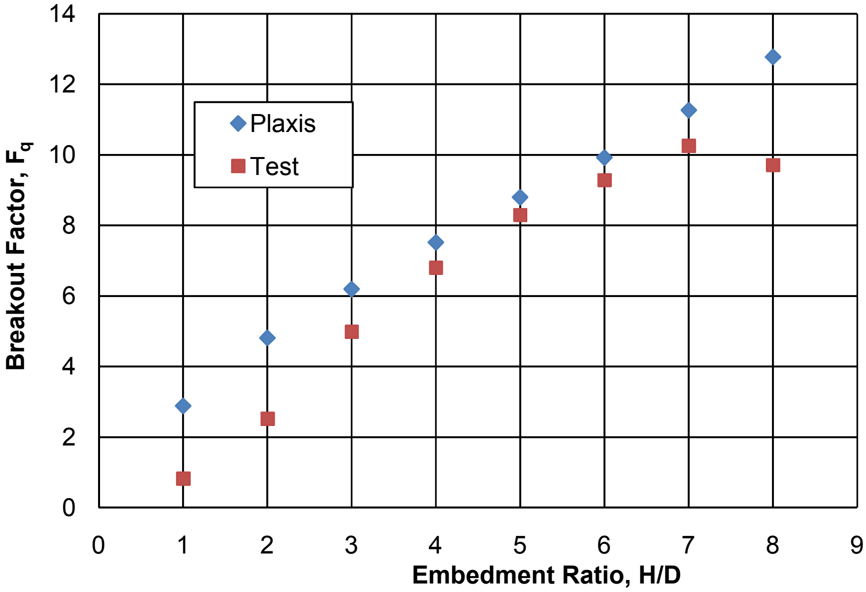

Figure 5. Comparison of numerical and experimental results on breakout factor F_q for anchors in loose sand.

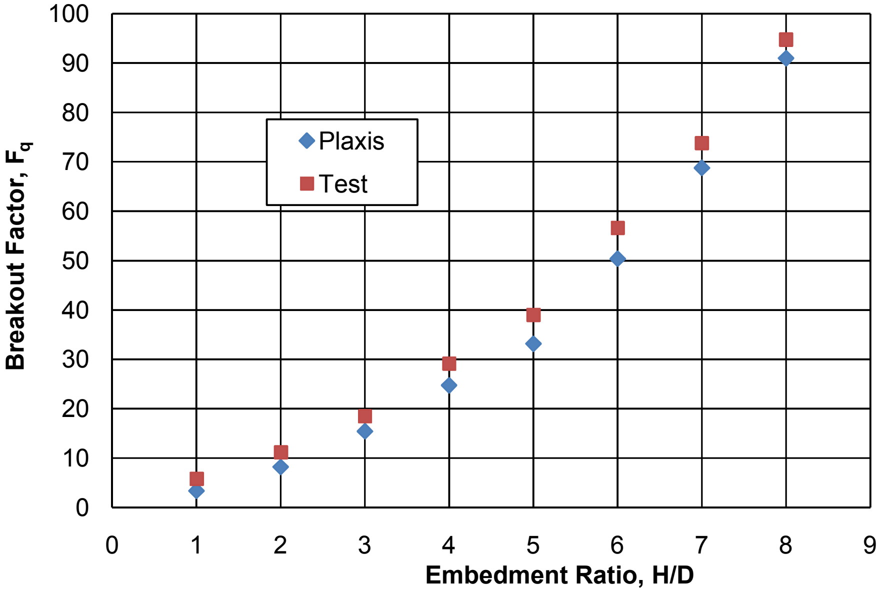

Figure 6. Comparison of numerical and experimental results on breakout factor F_q for anchors in dense sand.

CONCLUSION

Based on the laboratory and numerical investigations carried out on model anchors embedded at two different sand densities, the following main conclusions can be drawn:

- The uplift resistance of anchors in sand is strongly influenced by their embedment ratio and by the unit weight of the soil.
- Numerical analyses, using an elasto-plastic hyperbolic model (hardening soil), incorporating parameters derived from drained triaxial tests, gave results that closely match those from physical model tests.
- Relative density is the main parameter that affect the uplift capacity of anchor plates.
- The results from the finite element analyses are in very good agreement with experimental observations.
- The results demonstrate a relatively minor influence of mesh coarseness.

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