# Granular Anchor Pile System for Resisting Uplift: A Review

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**Abstract.** Granular anchor pile (GAP) system is a modified stone column in which the stone column is reinforced using an anchor rod with an anchor plate placed at the bottom. The anchor rod is embedded in the footing of the structure which rests on the stone column. This system prevents the uplift of the structure which may be caused by uplift forces like the presence of expansive soil below the footing, wind forces or buoyant forces. This paper presents a review about the application of Granular anchor piles, the conditions in which it can be used and the method of installation. A discussion on the parameters like length, diameter, soil type and its strength which influences the uplift capacity of the granular anchor pile is also given.

**Keywords:** Granular anchor pile, Granular pile, Anchor foundations, Ground improvement.

## 1 Introduction

### 1.1 Occurrence of uplift

The foundations of structures are required to transmit compressive forces safely to the subsoil. However, sometimes these may be accompanied with moments in addition to the lateral forces causing uplifting of foundations. The uplift of the foundation is normally caused by expansive soils, frost heave, wind, and hydrostatic force [1]. If the foundation of buildings especially lightly loaded civil engineering infrastructure is built on expansive soils they are subjected to alternate upward and downward movement due to expansion and shrinking when the soil absorbs moisture and dries respectively. This leads to distress in structural members such as columns, walls, and flooring, resulting in unsightly cracking. Uplift forces also act on the foundations of structures such as dry docks, basements, and pumping stations that are constructed below the fluctuating water table due to hydrostatic forces. Structures like transmission towers and tall chimneys are subjected to wind effects which cause a considerable amount of uplift forces under their foundations. The occurrence of uplift under the foundations if left unchecked causes irreparable damage to the building [1]. In expansive soils, some of the techniques used to reduce the heave due to expansion are sand cushion method, cohesive non-swelling layer method, physical alteration method, chemical alteration, and under-reamed piles. In soft soils and weak deposits the under-reamed pile, driven or cast in-situ piles are used to resist uplift.

### 1.2 Granular Anchor Pile (GAP)

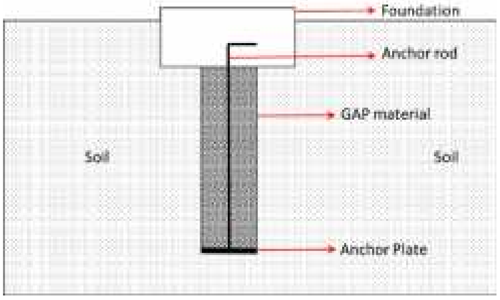

**Fig. 1.** Cross-sectional details of GAP foundation

A new tension resistant foundation technique was proposed by Phanikumar [2] called Granular anchor pile (GAP) in which a conventional granular pile or stone column is converted into a tension-resistant foundation by providing a reinforcement bar of suitable strength in the middle of the pile and the bottom end of the reinforcement is connected to a steel anchor plate or concrete pedestal and the upper end is fixed to the footing as shown in fig. 1. Kumar [3] extended the research of uplift capacity of GAP to cohesionless and cohesive soils using both laboratory and field tests. GAP has been found to control uplift forces significantly in expansive soils, soft clay, and loose sand deposits through extensive research conducted through laboratory scale and field scale tests. A number of numerical studies also show that granular anchor piles are an effective method to control uplift of foundations. This paper presents a review of the work carried out by researchers on different aspects of the GAP.

### 1.3 Mechanism of failure and uplift resistance of GAP

Most research available is concentrated on the study of GAP in expansive soil and soft soils. Therefore the mechanism of uplift resistance discussed in the literature is in terms of the GPA and its interaction with the surrounding expansive or soft soil. When the uplift force acting on the building is transferred to the foundation which is connected to GAP, it is resisted by the weight of GAP acting in a downward direction and the friction along with the pile-soil interface [4–6]. If the GAP is installed in expansive soil, the swelling of the soil further enhances the uplift resistance of the GAP by confining it radially and thus increasing the friction along the surface of the pile [4–7]. The granular material also plays an important part due to its dilatancy [8]. The failure mode of the short GAP and long GAP is either shaft failure or bulging failure respectively indicating that the failure mode mainly depends on the length to diameter ratio of the GAP [9]. Though there is ample research on the uplift mechanism of the

GAP in the cohesive and expansive soils in terms of uplift load response, there is only limited literature that focused on the failure mechanism of GAP in cohesionless soils.

### 1.4 Installation of GAP in field

Kumar [3] conducted a field study on the GAP in cohesive and cohesionless soil. A borehole was made in the ground using a manually operated auger. Fresh concrete was deposited at the bottom using tremie pipe and the prefabricated anchor plate and anchor rod was lowered on the concrete followed by concreting the base again. The anchor plate and anchor rod assembly consist of a mild steel plate with a rod of the same material welded on to the plate and extra ribs to strengthen the plate. The concrete cover prevents the corrosion of the anchor plate and gives extra strength to the anchor. The concrete was allowed an initial setting time of 7 days before backfill-ing the borehole with a mixture of crushed stone material and sand. The granular material mixture charged into the borehole in equal volumes and was compacted using a steel annular hammer with a fixed height of fall and number of blows. A similar procedure has been adopted by different researchers in the field studies without the concrete cover of the anchor plate [5, 8–11].

The installation procedure used by Liu [12] in the field is similar to the installation of the dry vibrated stone column. A steel pipe with a precast concrete toe was driven into the soft soil up to design depth. Concrete is filled at the bottom of the pipe and compacted with the pipe withdrawn upward. A steel bar with end-plate and centralizer is placed on the compacted concrete and fresh concrete is again poured on the end base, this anchors the steel bar in position. The steel pipe is filled with granular material and as it is gradually pulled out, the material is compacted using vibration. This process is repeated until the pipe is fully withdrawn.

## 2 Experimental studies

### 2.1 Laboratory investigation

Kumar [3] investigated the effect of embedment ratio i.e. the length to diameter ratio, number and spacing of the GAP on the uplift load response and ultimate uplift capacity in medium dense sand. The diameter of the GAP was found to have a major role in increasing the ultimate uplift capacity. An embedment ratio of ten times the diameter and spacing of three times the diameter of the GAP was found to be optimum. A study on the oblique pullout capacity of the GAP was carried out by Singh [13]. The study was conducted by varying embedment ratio, number of GAP and the oblique pullout angles as 30°,45°,60°, and 90° with respect to pile axis. The experimental investigation on single and group of GAP in loose to medium dense sand revealed that the ultimate pullout and efficiency was a function of the embedment ratio of the GAP.the ultimate pullout capacity was found to decrease with increase in pullout angle. The rate at which the pullout capacity increased when the embedment ratio increase was found to be a function of the pullout angle with a high rate of increase in case of lower angles and almost constant rate of increase in case of pullout angle 90°. The efficiency of the pile group was observed to increase with embedment ratio and a decrease in spacing between GAP.

Phanikumar [2, 4] and Ibrahim [14] performed laboratory model tests on GAP installed in expansive clay beds to study the influence of length, diameter and relative density of the GAP and the dry unit weight of expansive soil surrounding it. It was found that that the GAP reinforced expansive clay beds undergoes significantly less heave and the rate of heave improved with respect to the expansive clay bed without GAP. The reduction in the heave increases with an increase in the surface area and relative density of the GAP due to friction resistance offered by the pile-soil interface. The reduction in heave was found to increase with an increase in the number of GAP and reduction of the spacing between them.

In the pilot tests conducted in the laboratory by Harikrishna [15], model GAP and concrete pile were installed in saturated expansive soil and expansive soil compacted to achieve maximum dry density at optimum moisture content. The tensile load at a constant speed was applied to the GAP and the concrete pile to determine their pullout capacity. it was observed that the pullout capacity of the GAP was three to four times that of a concrete pile. The higher pullout capacity was attributed to increased friction at the pile-soil interface due to the lateral displacement of the granular material of GAP.

Laboratory model tests were performed by Muthukumar and Shukla [16] to compare the heave reduction of expansive clay in a cylindrical due to the installation of GAP and Helical pile anchors (HPAs). The tests were conducted by varying the number of GAP and HPA as 0 (unreinforced expansive clay bed), 1, 2, and 3. In the case of HPA the helices were also varied as 1, 2 and 3. The expansive clay in the tank was slowly inundated with water and the heave was obtained using dial gauges. It was found that there was a reduction in heave for both the GAP and HPA installed expansive clay beds. There was also a reduction in heave with an increase in the number of helices of HPA. However, the GAP was more effective in controlling the uplift of the foundation than HPA with any number of helices. The GAP was found to have additional uplift resistance due to surrounding clay offering lateral pressure against bulging of the GAP.

Few studies have been conducted to incorporate geosynthetics with GAP to enhance its uplift resistance [4, 6, 16]. In the laboratory scale study carried out by Phanikumar and Rao [4], the effect of placing base geosynthetic above the anchor plate to form an integral part of the GAP was studied. The model study was conducted in expansive soil and two types of geosynthetics were used i.e. geotextile and geogrid. The diameter of the base geosynthetic was kept larger than the GAP. The confining media used to sandwich the base geosynthetic was varied as black cotton clay – geotextile/geogrid – bottom sand layer, fine sand – geotextile/ geogrid – fine sand, coarse sand – geotextile/geogrid – coarse sand and metal chips – geotextile/geogrid – metal chips. The interface friction angle between the confining media and the geo-synthetic was found out using shear box text by placing the geosynthetic at the failure plane. It was observed that the interface friction angle increased with increase in gradation of the confining soil medium. A higher interface friction angle was also seen in the case of geogrid with respect to geotextile. The expansive soil was first saturated to induce heaving in the soil and after 100% saturation is achieved the anchor rod of the GAP was pulled out with equal increments of load. High heave reduction along with short time was observed in the reinforced expansive soil. The ultimate pullout load of GAP with the base geosynthetic was at least 2.4 times that of the GAP without base geosynthetics. The pullout capacity of the GAP increased with increase in gradation of the confining medium due to the resistance offered by the confining medium and base geosynthetic. The resistance was more in case of the geogrid base than the geo-textile base.

Phanikumar [6] investigated the effect of placing geogrid layers inside the GAP at a distance from the anchor plate. The number of geogrid layers (0,2,3 and 4), spacing and the location of bottom geogrid from the anchor plate were varied and the effect on heave and pullout behavior of GAP was studied. The diameter and embedment depth of the GAP were kept constant. The GAP was installed in expansive soil. The GAP was tested in both heave and pullout condition. It was observed that as the number of geogrid layers increases the heave of the clay bed reduced and the time takes to achieve the equilibrium heave also decreased. The heaving also reduces with the reduction in the spacing of the geogrid layers. This reduction was attributed to the confining and interlocking effect of the geogrid layers which resists the bulging and lateral spreading of the GAP material. It was observed that the pullout capacity of the GAP increased as the number of geogrid layers increase and the space between them decreased. The closer the bottom geogrid layer is to anchor plate the better was the pullout capacity. This was also attributed to the confining and interlocking effect of geogrid layers.

Muthukumar and Shukla [16] studied the effect of the geosynthetic encasement and its stiffness on the heave reduction capacity of single and group of GAPs. It was observed that the heave decreased with an increase in the number of GAPs. The encasement of GAPs leads to more than 50% heave reduction than non encased GAPs. This was true for any given number of GAPs. The increase in the stiffness of the geosynthetic encasement also reduced the heave. The encasement of the GAP leads to resistance against bulging failure thus increasing the uplift capacity. The increase in stiffness also helps in providing higher hoop stress to confine the GAP material.

## 2.2 Field studies

Kumar [3] conducted an extensive field study in both cohesionless and cohesive soils. A constant diameter of 0.3 m and spacing of 3 times the diameter for a group of GAP has been adopted for the field study. The results of uplift tests on a group of GAP showed that the ultimate capacity of the group was highly dependent on the number of GAPs in the group. The data showed that the ultimate capacities of the two and four number GAP group are almost equal to the ultimate uplift capacity of the single GAP multiplied by the number of GAPs in the group. In the study conducted in a cohesive soil, an embedment ratio of 13 was found to be optimum. The increase in embedment ratio played a minor role in the increase of the ultimate uplift capacity. However, the diameter and number GAP in a group played a significant role in the increase of uplift capacity. The ultimate uplift capacity of the 2 GAP group of embedment ratio 20 in cohesionless was almost 3 times more than in cohesive soil. Similar comparisons also suggest that the GAP system is more effective in cohesionless soil than cohesive soil.

Liu [12] conducted a field research study on the performance of two prototype GAPs installed in a land newly reclaimed from the sea for the construction of sewage pools. Repeated compression and tension cycle tests were carried out on the GAP which was installed in mostly soft soil layers. The length and the diameter of the prototype GAP were 17m and 0.5m respectively. The anchor rod of the GAP was fitted with load cells at top, middle and bottom portions and load transferred on to the rod was measured during the compression and tension cycles. The tensile load applied during the test was 50% of the calculated ultimate uplift load i.e. 150 kN and a compressive load of 180 kN. The test results indicate that the GAP was able to perform similar to the ordinary stone column under compression and at the same time resists tensile loading with undergo-ing large plastic displacements. The GAP system was later implemented to counter the cycling loading that takes place under sewage pools as they are filled and emptied.

Rao [7] and Phanikumar [5] conducted pullout tests on field scale GAP installed in expansive clay beds of depth 1m. The clay bed was prepared by compacting expansive clay at a water content of 15% in a pit. The diameter of the GAP was varied as 100, 150, and 200 mm and the length was varied as 500, 750, and 1000 mm. The expansive clay bed was flooded with water and allowed to heave and once the saturation was reached pullout test was conducted. The displacement of the top of the GAP during heaving was noted. The results showed that the heave of the GAP rein-forced bed reduced by 70, 87 and 92% for full depth GAP of diameter 100, 150, and 200 mm respectively when compared to unreinforced expansive clay bed. The time taken for achieving the full saturation and heave equilibrium reduced drastically in case of GAP reinforced expansive clay beds which was attributed to increased permeability of the GAP material. The pullout load increased with increase in the embedment depth indicating that the uplift resistance depends on the surface area of the GAP. The test was also carried out on a group of GAPs by keeping the diameter and length as 150 mm and 1000 mm respectively. During pullout test the center GAP of the group was loaded. When the GAP in the group was tested and compared to a single GAP it was noted that the GAP in the group performed better. This was due to high lateral swelling pressure and arching action in the group of GAP. Phanikumar [5] studied the undrained shear strength, penetration resistance and variation of heave with a depth of the reinforced and unreinforced expansive clay beds. Cylindrical samples from 25, 50 and 75 mm from the top of the saturated expansive clay bed were retried and conducted unconfined compression tests to determine the undrained shear strength. The undrained shear strength of the reinforced expansive clay bed was higher because of the increase in density as the heave was controlled in GAP reinforced clay beds. The poor permeability and uncontrolled heave lead to lower undrained shear strength in the unreinforced clay bed. Penetration tests were also conducted using a proctor needle up to 25 25, 50 and 75 mm from the top of the saturated expansive clay bed. The penetration resistance of the reinforced expansive clay beds was higher than unreinforced clay bed. Thus penetration tests result verified the results of the unconfined compression tests. The heave of the expansive clay bed was monitored at different depths and radial distances from the center of the GAP.

Rao [11] carried out field-scale plate load tests were conducted GAPs installed in expansive clay beds to study the compressive load response. The dimensions of the GAP was the same as that of the study done by Rao [7] and Phanikumar [5]. The tests were conducted in unreinforced expansive clay beds, reinforced expansive clays beds with single and group of GAP (3 GAPs). Two conditions of loading plate position were tested, one was composite ground position in which plate was placed on GAP as well as the expansive clay and in the other condition GAP alone was loaded. In the composite ground and GAP group study, the diameter and length were kept constant as 150 mm and 1000 mm. The embedment ratio and the diameter of the GAP were varied in the compression test of the single GAP. The compression tests were carried out after full saturation is achieved by flooding the clay bed. The results showed that the stress required for the settlement of 25 mm in the composite ground was more than twice that of the unreinforced bed and in case of GAP alone it is more than 3 times. When the group of GAP was tested, an improvement of 65% with respect to unreinforced clay bed was noted. The bulging of the GAP was observed to increase with the increase in the diameter of the GAP for a given length.

Sivakumar [9] performed the study of ultimate pullout capacity of granular anchors constructed in intact lodgement till and ground deposits. Uplift tests were also performed on the cast in situ concrete anchors to compare its performance with that of the GAP. Failure modes of GAP were also studied in detail along with proposing a new method for predicting the ultimate uplift capacity. The tests were carried out in two sites, in the first site the anchors were installed in stiff clayey silty sand with occasional gravel (mean undrained cohesive strength of 55 kPa) that was placed around 50 years ago, the second site soil consisted of stiff to very stiff, brown, slightly sandy clay of low plasticity. The first site was used to compare the cast in situ concrete anchors and GAP. The tests were conducted on the anchor of length 0.5, 1, 1.5 m with diameters 0.07and 0.15 m. The ultimate uplift capacity of the cast in situ concrete anchors and GAP was found to be almost same but the mode of failure was different. The GAP experienced ductile failure by undergoing a large amount of displacement while the concrete pile failed by sudden pullout failure with very less upward displacement compared to GAP. In short GAPs, the ground appeared to heave around the GAP indicating shaft failure. The longer GAPs failed by localized bulging at the base. The second site was used to understand the failure mode of GAP with respect to the surrounding ground surface. It was observed that short GAPs (length 0.5 and .45 m with diameter 0.196 and 0.148 m) failed in shaft resistance and the granular material at top of GAP and surrounding soil had undergone a substantial amount of heave. In case of long GAPs (length 0.8, 1.47 and 1.62 m with diameters 0.168 and 0.219 m) only marginal heaving was observed on the top of GAP and surrounding soil. The researchers proposed that the uplift load is resisted by shaft friction and localized bulging of GAP at its base. It was suggested that an embedment ratio of lesser than 7 resulted in shaft resistance failure and greater than 7 resulted in localized bulging failure at the base. Some tests were also carried out for double plate GAPs. The results indicated that a double plate anchor will have enhanced uplift capacity if the length of each segment should have an embedment ratio of greater than 7.

Harikrishna [15] carried out field testing to compare the performance of cast in-situ concrete pile and GAP in expansive soil. The pullout tests were conducted in both saturated (after 10 days of wetting the ground) and unsaturated condition. The length was varied as 1 and 1.5 m with diameters 100 and 150 mm. The results of the pullout tests indicated that the GAP had an uplift capacity of more than twice than that the cast in-situ concrete pile in both saturated and unsaturated conditions. This was attributed to the interlocking between the granular material of the GAP and the ides of the borehole. The pullout resistance of the GAP and cast in-situ concrete pile reduced due to saturation by 32% and 25% respectively. It was also noted that for the same area the diameter of the GAP plays a more important role than its length.

Krishna [15] conducted studies on the heave reduction of flooring panels using a combination of CNS layer and GAP. Five flooring panels 2.5 cm thick mortar of 3 m by 3 m size with five types of foundations were constructed in expansive soil ground. Five types of foundation were constructed, they were 0.5 m thick CNS cushion layer, a 9 group granular column of 0.2 m diameter and 0.6 m depth, a 9 group GAP of the same dimension as that of granular column, a combination CNS layer and group of granular column and an untreated 100 mm thick murrum compacted. The constructed flooring panels were cured for 10 days and flooded with water for 100 days. The seasonal movements of flooring panels were monitored for 4 years. It was noted that the GAP foundations performed excellently with respect to reduction of the heave. A heave reduction of 89% could be achieved when the flooring is provided with GAPs. The heave could be reduced to 92% when a combination of GAPs and CNS cushion is used.

## 3 Numerical studies

Ismail [17] carried out three-dimensional finite element analyses of a typical double-story building constructed over a system of granular pile anchor foundation system in a reactive soil. Both heave and shrinkage were modeled by applying equivalent volumetric strains to the affected area. An analysis of the building resting on pad footings with and without the GAP was done and the results were compared. The Mohr-Coulomb (MC) model was used to model the reactive soil and Hardening Soil (HS) model was used to GAP material and the underlying dense sand. The comparisons were made for the top beams of the central frame of the building. The results in terms of induced deformations, angular distortions and bending moments due to heave and shrinkage of the reactive soil were analyzed. It was observed that the maximum vertical displacement of 6.7 mm developed in the top central beams of the building due to heaving of the soil has been eliminated due to the use of foundation with GAP. It was also noted that the GAP foundation highly reduced the angular distortion and bending moments developed in the top beams. The results from the finite element modeling concluded that GAP foundation can be potentially used to reduce the destructive effects of expansive soil on the building.

Kranthikumar [18, 19] undertook extensive field scale study on the GAP in cohesionless soil using the finite element analysis software PLAXIS 3D. The studies were conducted on single and group of GAP by varying the length, diameter, relative density of the surrounding soil, the elastic modulus of the surrounding soil, number of GAPs in the group, compaction effects and the depth of water table. The Mohr-Coulomb (MC) model was used to model the cohesionless soil. It was concluded that the uplift resistance increases with an increase in the length and diameter of the GAP. An economic embedment ratio of 10 was proposed. It was noted that the relative density of the surrounding soil had a considerable effect on the ultimate uplift capacity. The efficiency of the group of GAP was found to decrease with an increase in the number of GAP for constant spacing due to overlapping stresses. The compaction effect on the GAP and surrounding soil during construction if considered during the modeling of GAP led to increases ultimate uplift capacity. The increase in water table level was found to decrease the uplift capacity. The two failure mechanisms identified were shaft failure and bulging failure.

Abhishek and Sharma [20] modeled GAP installed in expansive clay bed to study the length, diameter, elastic modulus of soil and pile, spacing and efficiency of a group of GAP, and effect of GAP construction. The GAP and clay bed was modeled in a laboratory scale with soil and GAP material defined using the Mohr-Coulomb (MC) model. The results from the models showed that the ultimate capacity of GAP increased with an increase in length and diameter. This was attributed to the self-weight of pile and friction developed along the pile-soil interface. The increase in the modulus of surround-ing soil lead to increase in uplift capacity but this was not of linear nature. Optimum spacing of 2.5 times the diameter of the GAP was proposed based on the results from the modeling of the group. The efficiency of the group of GAP was found to increase up to 10 times the diameter after which it decreased, thus it was proposed as an optimum embedment ratio for group pile.

## 4 Conclusions

The following are the conclusions from the review of the literature on GAP.

- The GAP system is a cost-effective foundation method that can be used in all types of soils to counter uplift forces and achieve heave reduction. The field and laboratory scale studies suggest that GAP is at par or better than currently used tension resistant foundation techniques like concrete anchor pile and screw pile. The compression tests on the GAP showed that it behaves similar to an ordinary stone column in soft soil.
- The uplift is resisted by the weight of the GAP and the friction developed at the soil- pile interface. The GAP installed in expansive soil uplift is also resisted by the lateral swelling of the soil. The two types of failure observed in GAP were shaft failure and localized bulging failure at the base of the GAP. Shaft failure was observed in short GAP and the localized bulging failure occurred in long GAP.
- The installation technique used in the field were of two types. One method was similar to the installation of the dry vibrated stone column and the other is similar

to rammed stone column installation without vibration. It was noted that during field installation it is better to give a proper concrete cover to the anchor plate to strengthen it and prevent corrosion.

- The ultimate uplift capacity of GAP depends on its embedment ratio i.e. the length to diameter ratio, relative density and elastic modulus of the surrounding soil and GAP material, level of the water table and degree of saturation of the surrounding soil.
- An embedment ratio of 10 to 13 is considered as the optimum embedment ratio after which there is no significant increase in ultimate uplift capacity. The diameter of the GAP plays a more important role than the length in affecting the uplift capacity of the GAP. The increase in elastic modulus and relative density of surrounding soil and the GAP material results in an increase of uplift resistance. The increase in moisture content decreases the uplift capacity of the GAP.
- The efficiency of a group of GAP decreases with spacing due to the overlapping of stresses. A spacing of 2.5 times the diameter was found to be optimum in cohesionless soil. Higher heave reduction was noted in the case of a group of GAP installed in expansive soil.
- The uplift capacity of the GAP can be improved by using geosynthetic encasement, geogrid layer inside the GAP and by increasing the number of plates. However, more studies are needed in this regard.
- The performance of the GAP in expansive soil is well documented. There is a shortage of research literature in the application of GAP foundation under structures that are prone to uplift failure.

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