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SUSTAINABILITY OF COMBINED VACUUM AND SURCHARGE PRELOADING

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ABSTRACT:

This paper presents a review of combined vacuum consolidation and surcharge preloading which is arguably more sustainable approach to soft-soil ground improvement than other strategies in reducing post-construction settlements. Vacuum consolidation has become more prevalent with technological developments in vertical drains, pumps and geosynthetics. Satisfactory vacuum pressures can be sustained at greater depths and for longer periods than in the recent past. Soft soil deposits may experience different issues depending on whether vacuum or surcharge preloading is employed. Surcharging alone may lead to outward lateral deformations and shear failure whereas vacuum alone induces inward lateral deformations, producing crack formation along the boundaries of the treatment area. By balancing these two approaches, respective outward and inward ground movements can be minimised.

INTRODUCTION

Vacuum consolidation usually involves applying a vacuum pressure into ground that has been protected from ground-surface pressure losses to atmosphere by a sealing membrane. The vacuum pump produces a negative pressure (with respect to atmospheric pressure) in a permeable soil cushion, located directly beneath the membrane, and along prefabricated vertical drains (PVDs) installed within the ground mass under treatment (Fig. 1). For soft clays, vacuum pressures as high as 90 kPa may be achieved in practice, although 80 kPa is typically considered for design purposes (Chu et al., 2008). Since the 1980s, improvements in associated technologies have brought about increased interest in the vacuum consolidation technique. Acceptable vacuum pressures can now be maintained for longer periods and to greater depths, with two ways of developing these vacuum pressures in the ground (Chai et al., 2008):

- Applying a vacuum pressure below the sealing membrane that covers the ground surface (i.e. membrane system, Fig. 1);
- Alternatively an existing surface or subsurface clayey-soil layer, where present, may be used as an effective sealing layer, in which casethe vacuum can be directly applied to each PVD via a geosynthetic cap (i.e. membrane-less system).

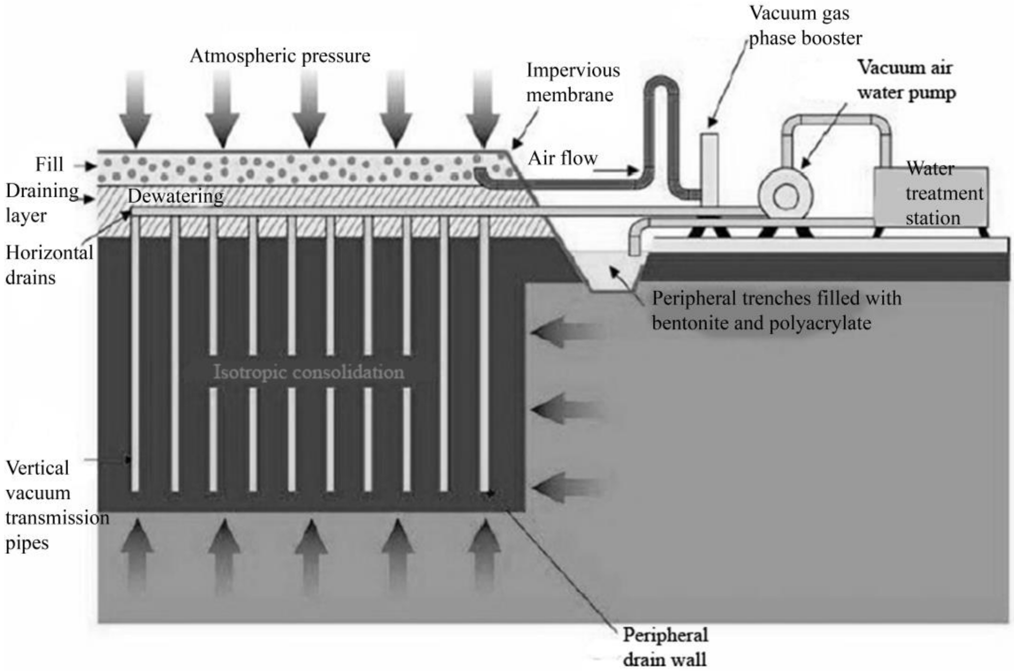

FIG. 1. **Schematic of typical membrane vacuum-consolidation system (Masse et al., 2001).**

SUSTAINABILITY

Sustainability plays a pivotal role in the development of new and existing engineering infrastructure schemes. As geotechnical aspects are often particularly resource intensive, the profession can significantly influence the sustainability of infrastructure development due to its position early in the construction process. Vacuum consolidation, either employed alone or in combination with surcharge preloading, has the potential to become a sustainable ground improvement strategy that is economical, both in terms of execution time (relative to surcharge preloading alone) and cost. In dealing with highly compressible, low permeability soils, a lengthy period is usually required to achieve near/full primary consolidation in-situ. The surcharge loading required to ensure such deposits undergo acceptably low amounts of post-construction settlement are often so large that, in maintaining an adequate factor of safety against slope instability, it may prove too time-consuming for the safe application of the necessary fill layers. The introduction of PVDs into the ground artificially reduces drainage path lengths, thereby significantly speeding up the consolidation process. Use of the vacuum consolidation technique in combination with surcharge preloading and PVDs can further enhance the efficiency of such ground improvement works (Chu et al., 2000, Indraratna, 2010, Mesri and Khan, 2012). The major advantage of the vacuum preloading technique is that the full vacuum pressure can be instantaneously applied, without risk of adversely affecting the factor of safety on slope instability.

Evaluation of the carbon footprint for a particular work activity is one of the first steps towards associated reducing greenhouse gas emissions. Emissions in the construction sector arise from processing of raw materials, product manufacture, waste and transport of materials, personnel and equipment (Kirsch and Bell, 2013). Calculations can be used to compare different geotechnical processes, which can be important in trying to reduce/minimise the total carbon dioxide equivalent for a given project. From comparative databases (e.g. EA (2010), GEMIS (2010)), it is evident that the energy requirement for manufactured construction materials (cement, steel, etc.) has a much larger impact compared with other emission sources listed. From experience of full-scale test embankments in Thailand, China and Australia, Indraratna et al. (2010) demonstrated key sustainability advantages of vacuum preloading over alternative ground improvement strategies. For instance, for three different sites considered, the carbon footprint arising from vacuum consolidation was compared against a pile foundation solution (Table 1). Carbon emissions arising from pile foundations were much higher mainly on account of this method's reliance on concrete and steel inputs.

Table 1: Carbon emissions for different ground improvement strategies (Indraratna et al., 2010).

Method	Site	Suvarnabhumi Airport, Thailand	Tianjin Port, China	Ballina Bypass, Australia
Vacuum consolidation	Duration (day)	150	120	300
	Carbon emissions (kg/m^2)	20.4	16.3	40.9
Pile foundation	Pile length (m)	15	20	25
	Concrete (kg/pile)	1131	1508	1885
	Carbon emissions (kg/m^2)	625	833	1041

The vacuum method is considered to be environmentally sustainable compared to alternatives since (Indraratna et al., 2010, 2012a):

- Compared with surcharging alone, reduced surcharge loads for vacuum-assisted preloading means less fill material must be imported onsite;
- Chemical residues are not introduced and left in the treated soil, although the PVDs remain in the ground post-treatment. Alternative methods such as cast-in-situ concrete piles or cement, gypsum and lime treatments can increase groundwater alkalinity locally and may severely harm subsurface life. Apart from effects on groundwater, leaching of this alkaline water to rivers or lakes also has the potential to harm natural habitats of fish and other freshwater organisms;
- Carbon emissions are approximately 30 times smaller compared with an equivalent pile foundation solution;
- Associated noise levels are generally acceptable compared, for example, against ground-works involving driven piles.

While significantly enhancing the environmental sustainability of a project, choosing vacuum-assisted preloading over surcharge preloading alone can also potentially reduce the cost of ground improvement by approximately 30%, largely on account of the time saved in reaching the full design preload. This figure is based on local prices of electricity and materials available at the time (Yan and Chu, 2003).

Recent advances in numerical modelling are also likely to improve the design efficiency of soft-soil ground improvement schemes. Although the concept of vacuum consolidation has been in existence since the 1950s, it has only become economical enough to apply in practice over the past 25 years. It is reasonable to expect that as analytical techniques improve and more experience is gained through different projects and for different ground conditions, so the associated costs, time and resource requirements will reduce. For instance, with greater documented experience of vacuum consolidation applied to soft clay deposits, models for predicting the response of similar ground conditions to vacuum consolidation, with or without surcharge preloading, will become more reliable. Hence the amount of fill material required onsite can be reduced and a shorter period will also be required in achieving near/full consolidation. Discrepancies between predicted and actual performance of the vacuum consolidation technique may arise from difficulties in predicting the impact of smear effects on the PVDs and well resistance (Indraratna et al., 2012b, Griffin and O'Kelly, 2014), along with incorrect assumptions regarding soil behaviour and the vacuum pressure distribution achievable against increasing depth. Numerical models have achieved improved accuracy, although remaining discrepancies between predictions and field measurements of pore pressure and settlement for vacuum-assisted preloading require further attention.

IMPROVEMENTS IN VACUUM CONSOLIDATION TECHNOLOGY

A number of issues must first be addressed for successful application of the vacuum preloading method in the field (Masse et al., 2001), including:

- The zone directly beneath the sealing membrane should not be saturated in order to ensure the drainage system operates effectively throughout the vacuum period;
- The membrane must be properly sealed and anchored around the perimeter of the treatment area and seepage from surrounding ground into the vacuum area should be avoided;
- The system must be free of leaks, especially at connections and across the membrane area.

For decades after its introduction, vacuum preloading was not applied in practice due to issues of maintaining an adequate vacuum pressure at depth throughout the treatment period. It was only with the introduction of higher efficiency vertical drains and sealing membranes, along with improved construction techniques, that the method has become more widely used in practice. It has also become more feasible to execute the method in various ground conditions as the mechanism of vacuum preloading has become better understood and vacuum pumping, monitoring and analytical design methods have developed and improved (Dam et al., 2006).

According to Qiu et al. (2007), in early vacuum preloading applications, vacuum pumps connected to a system of pipes and drains were used for providing suction and separating the air-water mixture expelled from the ground mass under treatment. However, the technique could not be widely applied on account of difficulties with air-water separation and poor sealing achievable along in-situ boundary conditions. For instance, in China, the technique could not be applied effectively until jet pump technology was introduced (Qiu et al., 2007). Today, high-efficiency vacuum pump systems, including a discharge pump, are used to apply negative pressures to the ground mass and discharge air and water out through a system of pipes and drains (Dam et al., 2006). The conventional vacuum pump has been replaced by a 48-mm diameter jet pump (7.5 kW), propelled by a centrifugal pump; a system that is capable of generating vacuum pressures in excess of 90 kPa (Dam et al., 2006). The vacuum system shown in Fig. 1 consists of a specially designed high-efficiency vacuum pump (generating up to 80 kPa suction) that acts solely on the gas phase, in combination with a conventional vacuum pump that allows liquid and gas suction.

The suctions a vacuum pump is capable of generating are rarely matched by the actual vacuum transmitted into the ground. Choa (1989) noted that vacuum consolidation substantially diminished in its effectiveness at depths greater than 14 m below ground surface level (bgl), despite the vertical drains extending to 20 m bgl. Bergado et al. (1998) observed that the vacuum pressure achieved in soft Bangkok clay at 15 m bgl was only 25% of that applied at the ground surface, even though the PVDs had been installed to this depth. However, higher vacuum pressures and greater treatment depths have become achievable. For instance, Chu et al. (2000) reported that for a 20 m thick, very soft clay deposit, the applied vacuum pressure was fully developed to 14 m bgl, with approximately 80% achieved at the base of this deposit. Prescribed minimum vacuum pressures recommended in practice of 60 kPa (for Japan) and 80 kPa (for China) can now be achieved, with 90% efficiency levels sometimes reported. For example, on one Japanese road project involving soft clay and peat deposits, the inclusion of a high efficiency air-water separation system produced vacuum pressures of 80–95 kPa (Dam et al., 2006).

Improvements with regard to vertical drain technology (including development of more permeable drain materials (Dam et al., 2006)), have led to the wider application of flexible PVDs, instead of sand drains (in France and South Korea) and cylindrical pipe drains (in Belgium), which had previously been more widely used for many years. PVDs have replaced circular drains primarily because they offer a more balanced distribution of vacuum pressures over the treatment depth (Chu et al., 2008) and they also have reduced comparatively in unit cost (Indraratna, 2010). PVDs can also be relied upon to continue performing, even under high surcharge loads, whereas sand drains are more vulnerable to local shear failure arising from the large settlements typically experienced by such soft deposits (Chu et al., 2008).

LATERAL DISPLACEMENT

Estimation of the lateral ground displacement near the perimeter of the treatment area is an important design consideration, particularly when the preload area is in close proximity to existing buildings/structures. In built-up areas especially, limiting lateral deformations induced by geotechnical engineering activity is important and can often be a critical factor in design (Ong and Chai, 2011). The lateral displacement of a soil element near the boundary of the vacuum treatment area depends on its relative depth below ground surface level and also its distance from neighbouring vertical drains. In the central area of the ground mass under treatment, each drain only affects the soil column centred on that particular drain (i.e. 1D condition prevails) and hence the unit cell method applies (Masse et al., 2001). However, nearer the perimeter of the treatment area, the interaction and hence influence of drains on adjacent soil columns can be significant. In this region, surcharge loading alone induces shear stresses in the ground that tend to cause outward lateral displacements (see Fig. 2(a)), with evidence of ground heave possible beyond the embankment toe (Indraratna and Rujikiatkamjorn, 2008), and which may potentially lead to shear failure occurring. In contrast, vacuum consolidation alone induces inward lateral displacements since it introduces an isotropic consolidation pressure to the soil mass (Fig. 2(b)). Hence, surface tension cracks may develop along the perimeter of the treated area, but without the potential risk of shear failure occurring. Indraratna and Rujikiatkamjorn (2008) suggested that for soft clays under vacuum preloading alone, surface settlements may occur to as much as 10 m distant from the perimeter of the area under treatment.

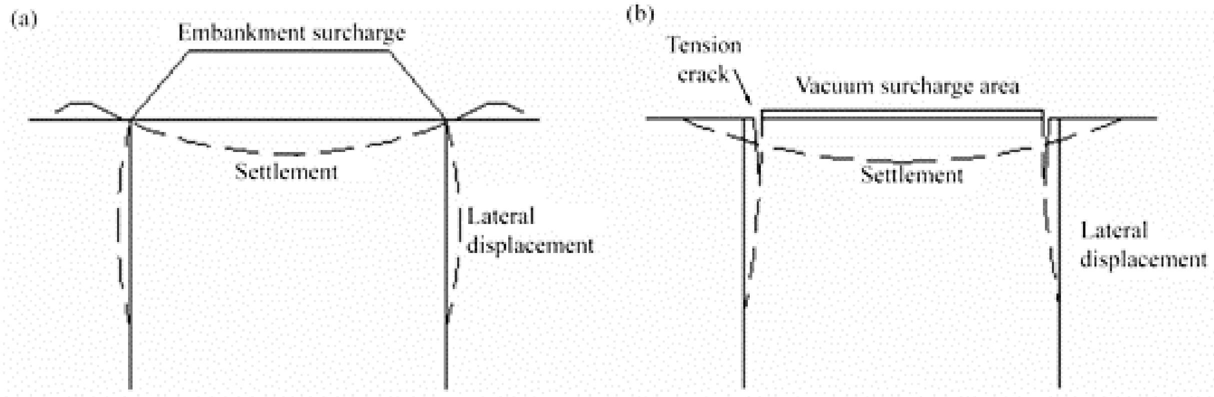

FIG. 2. Lateral deformation of ground under (a) embankment load alone and (b) vacuum consolidation pressure alone

Under combined vacuum and surcharge preloading, the net lateral displacement can be reduced (Indraratna et al., 2011) and, in theory, a 1D compression response achieved. However, the maximum value of lateral displacement due to embankment loading usually occurs at depth beneath the crustal layer, whereas under vacuum loading, the maximum inward movement occurs close to the ground surface. Therefore, since the mechanisms of lateral displacement for preloading under surcharge alone and vacuum alone are different, even the optimum combination of the two does not necessarily result in zero lateral displacement being uniformly achieved over the full depth profile (Chai et al., 2013). Nevertheless, for most clays, a combination of 40% surcharge and 60% vacuum generally appears to reduce the overall lateral displacement to a minimum (see Fig. 3) (Indraratna and Rujikiatkamjorn, 2008). Similarly, results from Ong and Chai (2011) suggest that lateral displacement is maintained close to zero when surcharging accounts for approximately 44% of the total preload.

A method of computing the lateral displacement arising from a combination of vacuum and embankment loading for a soft clayey deposit has been developed by Chai et al. (2013). It gives a direct relationship between the maximum net lateral displacement and the ratio of index pressure, p_n (see Eq. 1), to shear strength.

$$p_n = p_{em} - (|p_{vac}| + p_{em})U \tag{1}$$

where p_{em} is the embankment pressure, p_{vac} is the applied vacuum pressure and U is the average degree of consolidation achieved in the PVD-improved zone by the end of embankment construction.

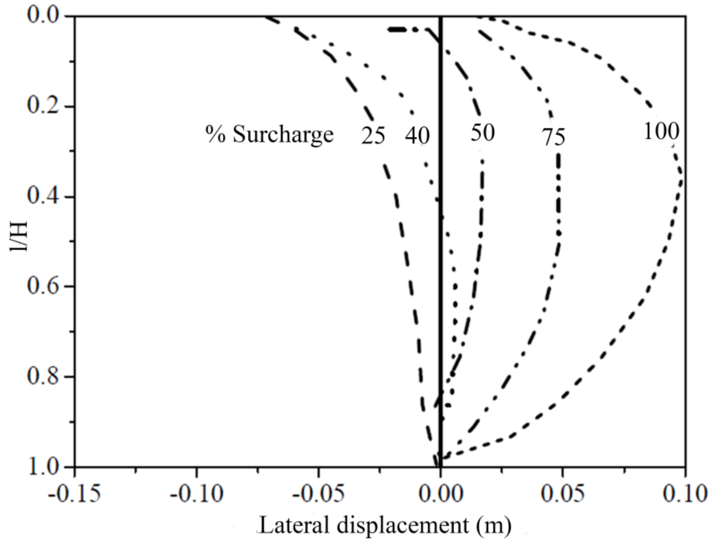

FIG. 3. Lateral displacement profiles under vacuum preloading for different percentage surcharge preloads. l/H = ratio of drain length to overall thickness of soil deposit (adapted from Indraratna and Rujikiatkamjorn, 2008). Note sign convention: inward displacement negative; outward displacement positive.

Ong and Chai (2011) found that the lateral deformations occurring under combined vacuum and surcharge preloading are influenced not only by the ratio of surcharge loading to vacuum pressure, but also by the rate of surcharge loading. They performed large-scale laboratory model tests, along with finite element analyses, to study the main factors affecting the lateral displacement response of soft clayey ground under combined preloading. Their findings suggest that:

- Outward lateral deformations increase with the embankment loading rate since the ground response becomes closer to an undrained condition under higher loading rates. Induced shear stresses are larger and hence lateral displacements tend to be greater;
- For a given loading combination and rate, inward or outward lateral displacement reduces with an increase in initial undrained shear strength;
- Outward lateral displacement generally increases with the ratio of surcharge load to vacuum pressure, in agreement with findings presented earlier in Fig. 3;

To simulate isotropic conditions experienced during vacuum consolidation, Robinson et al. (2012) developed a modified hydraulic-consolidation (Rowe cell) apparatus that incorporated a peripheral rubber membrane in order to allow all-round deformation of the soil cell. Using this apparatus, the role played by lateral deformation under vacuum consolidation could be better represented. The axial strains were observed to be significantly lower compared with 1D compression under an equivalent vertical stress applied using the same apparatus. Similar findings by Chai et al. (2005) showed that settlements are greater for soft soils under surcharge than under an equivalent vacuum, provided the applied surcharge is greater than the preconsolidation pressure.

Mesri and Khan (2012) proposed an empirical method for estimating the lateral displacement profile against depth, on the basis that a relationship exists between the lateral displacement occurring at a particular depth and surface settlement. It confirms the conclusion of Ong and Chai (2011) that the amount of lateral displacement depends on the soil compressibility as well as the loading condition. Since the lateral displacement (δ_s) and settlement (S_s) occurring at the ground surface under vacuum preloading both arise from consolidation of the soil deposit, it could be expected that some empirical correlation exists between them. One such correlation was developed based on field observations for nine case histories employing vacuum preloading (Fig. 4). The most typical δ_s/S_s ratio value of 0.36, together with the computed S_s value, can be used to estimate lateral displacement occurring at ground level close to the boundary of the treatment area.

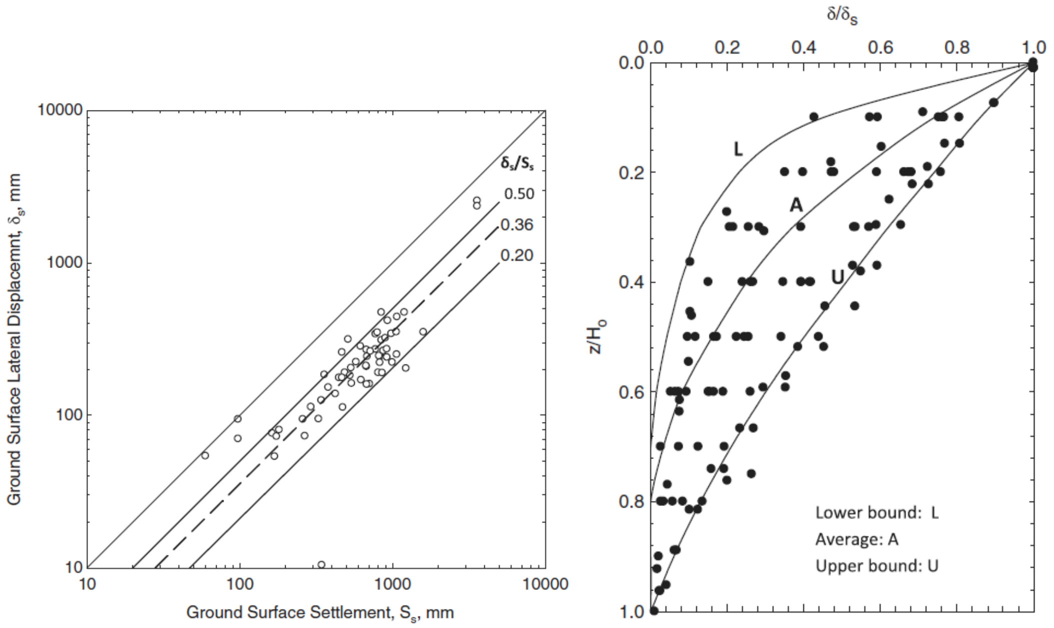

FIG. 4. Deformation response of vacuum-treated area: (a) Ground-surface lateral displacement at boundary plotted against ground-surface settlement at centre of treated area; (b) Ratio of lateral displacement (δ) to ground-surface lateral displacement (δ_s) at boundary against depth (Mesri and Khan, 2012). Note: H_o, initial thickness of soft soil deposit; S_u, undrained shear strength; z, depth below ground surface level.

The large spread in lateral displacement values against depth shown in Fig. 4(b) is indicative of soil profiles having different compressibility, pre-consolidation pressures and degrees of consolidation. Referring to Fig. 4(b), an estimate of the lateral displacement at the boundary of a vacuum-treated area may be obtained from the average (A) empirical correlation, with the likely displacement range obtainable from the lower (L) and upper (U) bounds.

SUMMARY

Combined vacuum and surcharge preloading with vertical drains can be considered as a sustainable ground improvement strategy in reducing post-construction settlements on account of its efficiency of construction time and costs compared with other approaches. Vacuum pressures can be applied immediately rather than in stages for surcharge preloading alone, but without the risk of geotechnical instability. Required amounts of surcharge fill to achieve near/full consolidation settlement in an economically-feasible period can also be reduced. Recent advances in numerical modelling are also likely to improve the efficiency of vacuum and surcharge preloading schemes. Other advantages over other ground improvement methods include: carbon emissions are reduced; chemical residues are not left in the treated ground and noise levels during construction/implementation are usually acceptable. Improvements in associated technologies mean that adequate vacuum pressures can now be maintained for longer periods and to greater depth. When applied independently, vacuum pressures or surcharge stresses each present a number of potential drawbacks. however, by combining the two, respective outward and inward lateral displacements can effectively be minimised, alleviating potential risks of ground movements causing interference to nearby foundations/structures, or in more extreme cases, shear failure occurring.

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