10 Mar 1991, 1:00 pm - 3:00 pm

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Proceedings: Second International Conference on Recent Advances in Geotechnical Earthquake Engineering and Soil Dynamics, March 11-15, 1991, St. Louis, Missouri, Paper No. LP14

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SYNOPSIS: The October 17, 1989, Loma Prieta earthquake subjected a number of solid waste or sanitary landfills to significant shaking. The performance of sanitary landfills during large earthquakes is of great interest to the public, state and federal agencies, and the landfill owners.

The observed performance of six sanitary landfills located within the Loma Prieta earthquake damage zone is compared with the performance predicted by a commonly used deformation analysis technique. The six landfills were inspected immediately after the October 17, 1989, magnitude 7.1 earthquake. Damage and evidence of slope movement, or lack thereof, was recorded. The mean peak ground accelerations were estimated and used in a deformation analysis as proposed by Makdisi and Seed (1977). The deformations predicted by the analyses are compared with the observed conditions and from the results of the comparison, a preliminary assessment of the analytical techniques and input parameters is made.

INTRODUCTION

The October 17, 1989, Loma Prieta earthquake resulted in about 9 seconds of strong shaking in the Monterey Bay and San Francisco Bay areas of California. The earthquake ruptured a segment of the San Andreas fault beneath the Santa Cruz mountains resulting in several billion dollars of property damage.

The earthquake subjected a number of solid waste or sanitary landfills to significant shaking. The performance of sanitary landfills during large earthquakes is of great interest to the public, state and federal agencies, and the landfill owners. California regulations require that landfill containment features be capable of withstanding shaking from the maximum probable earthquake. The U.S. Environmental Protection Agency's (EPA) proposed changes to 40 CFR Part 258 (RCRA Subtitle D) require that new municipal solid waste landfills located in a "seismic impact zone" be designed so that all waste containment systems resist the maximum horizontal accelerations for the site. Waste containment systems or features include liners, leachate collection and removal systems, and final covers. Significant landfill slope failures or displacements can potentially damage these containment features.

At present, the slope stability of sanitary landfills is generally evaluated by limit equilibrium slope stability analyses. Analysis input parameters include slope heights and geometry, landfill foundation soil properties, refuse unit weights, and refuse strength properties. Foundation soil properties are obtained by traditional soil mechanics techniques. Refuse properties are based on field data and on back-calculated refuse strength parameters (Converse, 1975).

The seismic stability of sanitary landfills is often evaluated by the modified Newmark method as proposed by Makdisi and Seed (1977). The Loma Prieta earthquake presents the rare opportunity to compare the predicted with the observed performance.

A number of sanitary landfills lie close to the Loma Prieta earthquake epicenter. The six landfills shown on Figure 1 were inspected for damage and deformation by engineers and geologists within three days of the October 17, 1989, earthquake. This paper compares the observed performance of the six landfills with the predicted seismic performances.

SITE CHARACTERISTICS

Geologic Setting

The San Francisco Bay area is characterized by highly variable and complex geologic conditions that broadly affect seismic ground response. The hillside terrain is supported at depth by well-indurated basement rocks of the Franciscan Complex and a separate complex of regionally metamorphosed rocks and granitic intrusives. This dual-core basement terrane is overlain in large areas by a thick section of relatively soft, clay-rich, Tertiary sedimentary rocks. Though highly variable, the sedimentary rocks generally consist of interbedded sequences of poorly to moderately indurated sandstones, siltstones, and shales. The valley floors and lowland margins surrounding the Bay and fronting the Pacific Coastline are underlain by young, alluvial and estuarine deposits.

For the purposes of determining seismic site response characteristics, the geology of the Bay area can be broadly grouped into (1) rock and rock mantled with shallow soils, (2) thick

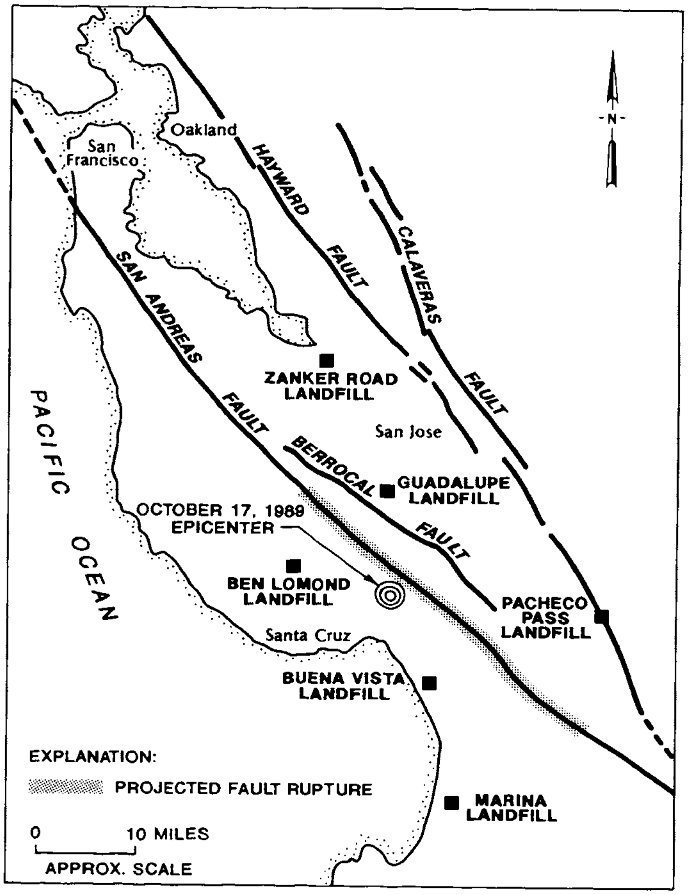

Figure 1

SELECTED SANITARY LANDFILL LOCATIONS WITHIN THE LOMA PRIETA EARTHQUAKE DAMAGE AREA

alluvium, and (3) soft, clayey estuarine deposits known locally as Bay Mud (Borcherdt, 1975). The geologic conditions of each site and the associated seismic response grouping are summarized in Table 1.

Estimates of Ground Motion

Values for mean peak horizontal ground acceleration were estimated for each site with data available from nearby strong-motion recording stations and existing attenuation relationships. To develop the estimated values, each site was first plotted on a map with the peak horizontal ground surface accelerations from strong-motion recording stations operated by the U.S. Geological Survey and the California Division of Mines and Geology Strong Motion Instrumentation Program (Maley et al., 1989; Shakal et al., 1989). Values from nearby strong-motion sites with similar geologic settings were compiled (Table 2).

Values for peak and mean peak horizontal ground acceleration were next calculated for each site using available attenuation relationships. Seven different relationships were used to develop a range of calculated values and to determine if any single relationship best fit the observed strong-motion data (Table 2). Ground motions for the Zanker Road Landfill were calculated with the "soft soil" relationships developed by Krinitsky (1988) and Idriss (1990). The calculated values were averaged and a standard deviation was determined for the data set. The range of calculated values and the average values were compiled with the strong-motion data (Table 2).

TABLE 1. Comparison of Preferred Mean Peak Horizontal Acceleration with Geologic Setting and Horizontal Distance to Project Rupture Surface

Site	Distance[1] to Epicenter/ Projected Rupture (km)	Geologic Setting	Preferred[2] Mean Peak Horizontal Acceleration (g)
Buena Vista	14/10	Alluvium	.40 ± .05
Ben Lomond	18/12	Rock	.40 ± .05
Guadalupe	20/8	Rock	.35 ± .05
Pacheco Pass	36/16	Rock	.20 ± .05
Marina	37/25	Alluvium	.15 ± .03
Zanker Road	45/27	Soft Soil	.23 ± .03

[1] Horizontal distance from the site to the epicenter and to the nearest point on the projected fault rupture surface.

[2] Estimated mean peak horizontal acceleration on nearby strong-motion stations, values calculated from attenuation relationships, and geologic and engineering judgment.

The values calculated from attenuation relationships were compared with the observed strong-motion data so that the reasonableness of the calculated values for each site could be evaluated. The calculated values compared well for the sites 20 kilometers or more from the epicenter; however, the calculated values for sites within this distance were significantly lower than the recorded values. Consequently, preferred estimates for mean peak horizontal acceleration were developed for the near-field sites (i.e., Buena Vista, Ben Lomond and Guadalupe) based primarily on data from nearby strong-motion stations, while the remaining sites (i.e., Pacheco Pass, Marina, and Zanker Road) reflect both the recorded data and the values determined from attenuation relationships (Table 1).

It should be noted that values for <u>mean</u> peak horizontal accelerations have been determined to be typically 12 percent lower than peak horizontal accelerations (Campbell, 1981). This reduction has been accounted for in the estimated preferred values for mean peak horizontal acceleration (Table 1).

FIELD OBSERVATIONS

The six landfills shown on Figure 1 were inspected in the days following the Loma Prieta earthquake. The observations made during these inspections, which concur with those reported by Orr and Finch (1990), are described in this section.

TABLE 2. Comparison of Available Strong-Motion Data and Calculated Horizontal Accelerations

Site	Closest[1] Comparable Strong-Motion Records	Calculated[2] Peak Horizontal Accelerations (g)	Average[3] Calculated Peak Horizontal Acceleration (g)
Buena Vista	.39 - .54	.31 - .44	.36 ± .05
Ben Lomond	.45 - .47	.24 - .36	.30 ± .05
Guadalupe	.28 - .45	.30 - .44	.36 ± .05
Pacheco Pass	.17	.17 - .30	.22 ± .05
Marina	.12 - .15	.13 - .21	.16 ± .03
Zanker	.21	.24 - .28[4]	.26 ± .03

[1] Peak horizontal accelerations (g) from nearby strong-motion recording stations with comparable geologic settings.

[2] Range of peak horizontal accelerations (g) calculated from attenuation relationships developed by Schnabel and Seed (1973), Joyner and Boore (1981), Seed and Idriss (1982), Idriss (1985), Campbell (1987), Joyner and Fumal (1988), and Krinitsky (1988). Values from Campbell (1987) are mean peak values.

[3] The peak horizontal ground acceleration and standard deviation derived from averaging of cited attenuation relationships.

[4] Values calculated from ground acceleration relationships developed for "soft soil" sites by Krinitsky (1988) and Idriss (1990).

Buena Vista Landfill

Minor cracking was noted on the southwest slopes of the landfill near where the catch line of the fill meets the natural ground surface. This landfill is a combination excavated module and above-ground fill. The biggest cracks were about 3 inches wide with crack sets traceable for about 100 feet in length. Cracking was also noted along an access road adjacent to the landfill and next to a slough channel.

Ben Lomond Landfill

Minor cracking was observed along the top of the landfill near the hingeline with the landfill slope. No other evidence of downslope movement was noted after the earthquake.

Guadalupe Landfill

Cracking with some apparent minor downslope or across-canyon movement was observed. Cracks had maximum openings of about 2 inches with crack sets extending more than 100 feet in length. Office trailers were also shaken off their foundations.

Pacheco Pass Landfill

Very minor cracking was observed along the crest of a 30- to 40-foot-high, unengineered earthfill located on top of an area of an old, inactive portion of the landfill. The cracks were up to about 1 inch wide. No other evidence of displacement was noted in the earthfill or at other locations at the landfill.

Marina Landfill

No surface cracks or slope failures were observed. Some apparent horizontal displacement was observed in rigid landfill gas control piping.

Zanker Road Landfill

No cracking or slope displacements to the landfill were observed. An on-site trailer and conveyor system located on the landfill were shaken off their foundations.

ANALYSES AND RESULTS

Material Properties and Methodology

The shear strength properties of sanitary landfill refuse-soil mixtures are not easily determined since the physical composition of the mixture makes it unsuitable for conventional laboratory strength testing, either as relatively undisturbed, or as fabricated samples. Limited information is available in the technical literature regarding refuse shear strength parameters. We have used shear strength parameters developed by Converse Davis Dixon Associates (1975) from a full-scale load test on an active sanitary landfill. The landfill slope was about 100 feet high with an approximate slope ratio of 1.5:1 (horizontal to vertical). More than 35 feet of earthfill was placed on the landfill in a 4-week period, with horizontal and vertical displacements monitored during placement and for an additional 2 months. The landfill slope did not experience a classical failure during this loading, but underwent relatively large vertical and horizontal displacements. The 1975 study developed refuse strength parameters by back-calculating the cohesion intercept (C) and the angle of internal friction (ϕ) needed to compute a factor of safety of 1.0 for the test slope. The calculated parameters ranged from C = 980 pounds per square foot (psf), ϕ = 10 degrees to C = 0 psf, ϕ = 26.5 degrees, and were presented as a graph of parameters needed to compute a factor of safety of 1.0.

For the analyses described in this paper, we have selected, unless noted otherwise, shear strength parameters of C = 400 psf and ϕ = 20 degrees. These parameters fall within the range presented in the 1975 study. We selected a total unit weight of 70 pounds per cubic foot (pcf) for the refuse and daily cover soil based on our experience with placement densities at several sanitary landfills.

We analyzed the static slope stability using limit equilibrium methods on the six landfills with the computer program CLARA (Hungr, 1988). CLARA uses Bishop's modified method of slices and allows searches for both circular and noncircular rotational surfaces. A sanitary landfill is believed to be a very irregular mass; however, for analysis, the landfill was assumed to be homogeneous. Critical failure surfaces passing through the wastes were therefore estimated to be circular.

Landfill deformations produced by the Loma Prieta earthquake were approximated by the simplified method of estimating permanent deformation of Makdisi and Seed (1977). This analytical procedure is based on the yield acceleration method developed by Newmark (1965). The analysis assumes that a slope or failure surface has a "yield acceleration" beyond which the potential failure mass will undergo permanent deformation. The yield acceleration (K_y) is the horizontal acceleration that reduces the factor of safety to unity in a limit equilibrium analysis. As shown on Figure 2, the deformations induced by an earthquake are a function of the ratio of the yield acceleration (K_y) to the mean peak ground acceleration (K_{max}) and the magnitude of the earthquake

Figure 2, developed by Makdisi and Seed (1977), is commonly referred to as a modified Newmark chart, and is widely used for seismic slope analyses. The development of the simplified analysis was based on finite element analyses and on the observed performance of earthfill embankments ranging in height from 75 to 150 feet for earthquake magnitudes of 6.5, 7.5, and 8.25. Since there is little information regarding the damping or amplifying properties of refuse, the analysis discussed in this paper uses estimates of mean peak acceleration at the base of the landfill.

The preceding paragraphs describe the general procedures and limitations of stability and deformation analyses of sanitary landfills. The following paragraphs describe the stability and deformation analysis results based on these procedures. In general, cross-sections for stability analyses were selected as those thought to be most critical on the basis of refuse fill depth, slope, and foundation conditions. For sites where earthquake-induced cracking was observed, sections were selected and analyzed where potential failure surfaces passed through the area of cracking.

Buena Vista Landfill

Buena Vista Landfill is an area fill about 9 miles south of the Loma Prieta earthquake epicenter. The estimated mean peak ground acceleration at the site was 0.40g. The site is underlain predominantly by weakly cemented sands and silty sand with some fine-grained materials. From a site-response perspective, the site is considered an "alluvial site." It has been in operation for more than 30 years.

Site development includes hillside excavations

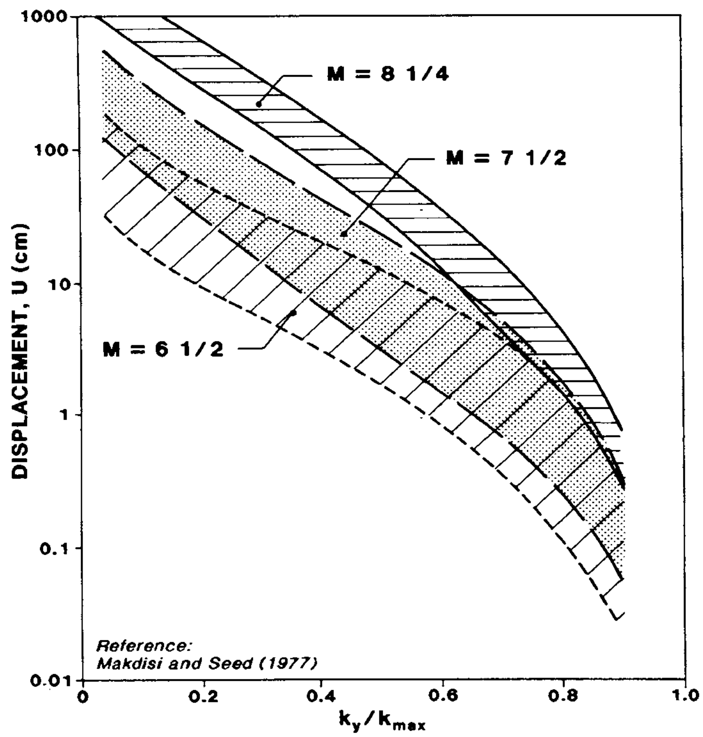

Figure 2
VARIATION OF PERMANENT DISPLACEMENT WITH YIELD ACCELERATION

up to about 80 feet in depth with waste disposal in the excavations and extending above the original ground surface. The maximum thickness of refuse fill is about 100 feet. Excavation slopes are 2:1 (horizontal to vertical); overall constructed landfill slopes are about 3.4:1 (horizontal to vertical). A compacted clayey soil base liner was placed under much of the landfill before refuse disposal. Laboratory triaxial shear tests of clay liner material indicate that when compacted, it is as strong or stronger than the refuse.

The minimum computed factor of safety for the landfill maximum section was 2.0. The computed yield acceleration was 0.26g. The computed permanent displacement for this landfill section ranged from 0.5 centimeters (cm) to 7 cm. No cracks or displacements were observed during the site inspection in areas of the landfill that would correspond to the section analyzed. Because of the behavior of landfill materials, it is uncertain that permanent displacements on this order would be manifested in the form of surface cracking or obvious bulging.

Minor cracking was observed along a landfill access road and near the landfill toe but away from a maximum landfill section. The cracking along the landfill access road is most probably associated with minor lateral spreading into an old slough that runs adjacent to the access road. Two hypotheses are being evaluated to explain the observed cracking along the landfill toe. The first is that the cracking is due to differential settlement between areas with deep and shallow deposits of refuse. This would be similar to the transverse cracking which is observable adjacent to the abutments in some large earthfill dams constructed in steep-walled canyons. The second hypothesis is that there may have been movement along a landfill-gas control membrane installed on the landfill excavation slope in the corner of the landfill where cracking was observed.

Ben Lomond Landfill

The Ben Lomond landfill is a canyon fill approximately 11 miles west-northwest of the epicenter. The site is underlain by a weakly cemented sandstone formation and can be considered a rock site for the purpose of evaluating seismic response. The estimated mean peak ground acceleration is 0.40g.

The landfill has a maximum refuse thickness of approximately 100 feet and an overall slope of about 3.8:1 (horizontal to vertical). The minimum computed factor of safety was 2.1 and the yield acceleration was 0.26g. The computed permanent displacements were between 0.8 cm and 7 cm. The minimum computed factor of safety and estimated displacements were for a relatively deep-seated failure surface.

To model a potential failure surface corresponding to the observed cracking on the landfill after the earthquake, a shallow potential failure surface was analyzed. This surface approached an infinite slope condition. The minimum computed factor of safety for the shallow surface was 2.9 or higher (as anticipated) than the deeper surface. The computed yield acceleration was 0.46g. Since the yield acceleration is greater than the estimated mean ground acceleration, no permanent displacements are predicted.

In order to evaluate further the apparent displacement (as evidenced by observed surface cracks) after the earthquake, the shallow potential failure surface was analyzed with refuse strength parameters of $c = 0$ and $\phi = 26.5$ degrees. With these parameters, the minimum computed factor of safety was 1.8 and the yield acceleration 0.20g. The predicted permanent displacement with these refuse strength parameters is 3 to 20 cm.

Guadalupe Landfill

Guadalupe Landfill is a canyon fill approximately 12.5 miles north of the Loma Prieta earthquake epicenter. The site is underlain by well-indurated sandstones, shales, and serpentinites. The estimated mean peak ground acceleration from the Loma Prieta earthquake was 0.35g.

The site has been used for waste disposal for more than 50 years. Initially, there was a burn dump near what is now the toe of the landfill. The first phase of landfilling concentrated on the north side of the canyon and the second phase, on the south side. The maximum refuse thickness is about 100 feet with the overall slope at maximum (critical) section about 2.5:1 (horizontal to vertical). The minimum computed factor of safety was 1.6 with a yield acceleration of 0.20g. The estimated permanent displacement was between 2 and 12 cm.

The pattern of cracks observed after the earthquake did not definitively indicate downslope movement of the landfill. The crack pattern suggested possible movement of the second phase of the fill toward the first phase, or cracking from earthquake-induced differential settlement of the landfill. A more thorough evaluation of the cracking is underway.

Pacheco Pass Landfill

The Pacheco Pass Landfill is approximately 22 miles east-southeast of the Loma Prieta earthquake epicenter and can be classified as a rock site for the purpose of evaluating seismic response. The estimated mean peak ground acceleration at the site was 0.20g.

Refuse filling began in 1963. At the time of the earthquake the landfill was approximately 125 feet high with an overall slope of about 3.6:1 (horizontal to vertical). The minimum computed factor of safety is 2.4 and the yield acceleration is 0.3g. Since the yield acceleration is greater than the estimated mean peak ground acceleration at the site, no deformation is predicted and none was observed in the landfill material.

Marina Landfill

The Marina Landfill is an area fill approximately 23 miles south of the Loma Prieta earthquake epicenter. The estimated mean peak ground acceleration at the site from the Loma Prieta earthquake was 0.15g. The original ground surface at the landfill site is generally flat. The ground-water level is within 5 to 10 feet of the original ground surface. The landfill's foundation consists mostly of loose to dense sand and silty sand with some sandy clay lenses. Liquefaction occurred in the general site area during the 1906 San Francisco earthquake and was observed about 2 miles north of the landfill site after the Loma Prieta earthquake. No evidence of liquefaction was observed during a site inspection after the Loma Prieta earthquake.

Stability and deformation analyses were performed on a recently completed landfill module. The section analyzed had a maximum fill depth of approximately 90 feet with 3:1 (horizontal to vertical) slopes. The minimum computed factor of safety for this slope was 1.9. The computed yield acceleration was 0.26g. Since the yield acceleration is greater than the estimated mean peak ground acceleration, the deformation analysis predicted no permanent displacements of landfill slopes. None were observed during the site inspection.

Zanker Road Landfill

The Zanker Road Landfill is an area fill located at the southern end of San Francisco Bay, approximately 28 miles north of the Loma Prieta earthquake epicenter. The site is on the fringe of the soft estuarine deposits called Bay Mud. The Bay Mud is typically a soft, silty clay to clayey silt. At the site, the Bay Mud overlies a complex formation of alluvial deposits consisting of stiff to very stiff silty to sandy clays and medium-dense clayey sands. At the site, Bay Mud is nonexistent to 20 feet thick or more. For the purpose of evaluating seismic response, the site was considered a soft soil site. The estimated mean peak ground acceleration at the site from the Loma Prieta earthquake was estimated to be 0.23g.

Refuse disposal at the site began in 1938. Because of consolidation of the Bay Mud from the landfill loading, the undrained strength of the Bay Mud underlying the landfill has increased from the typical values of 200 to 400 psf. Laboratory shear strength testing of landfill foundation soil samples obtained in 1989, before the earthquake, indicate that the Bay Mud foundation soils have an undrained strength of about 1,000 psf.

At the maximum section, the landfill is about 75 feet high (refuse thickness up to about 85 feet) with an overall slope of about 3.2:1 (horizontal to vertical). The minimum computed factor of safety for this maximum section was 1.7 with a yield acceleration of 0.14g. The potential failure surface passed through the landfill's foundation. The estimated permanent displacements were between 1 and 10 cm. No evidence of landfill cracking or deformation was observed following the Loma Prieta earthquake.

CONCLUSIONS

We have drawn the following preliminary conclusions based on our field observations and analyses:

1. In general, the Makdisi and Seed simplified procedures for predicting permanent displacements appear to be an appropriate tool for evaluating the seismic performance of sanitary landfill slopes. However, considerable engineering judgment is needed in evaluating the analyses.

2. Based on a comparison of recorded strong-motion data and the values of peak horizontal accelerations calculated from attenuation relationships, the existing attenuation relationships provide reasonable estimates for sites at distances greater than about 20 kilometers from the epicenter. At closer distances, the calculated values were significantly lower than the recorded data.

3. To be able to better assess the potential impacts of relatively small landfill deformations on some landfill containment features, a better understanding of both the static and dynamic stress-strain properties of sanitary landfill materials is needed.

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