Estimate the Magnitude and Nature of Distress the Various Structures Have Undergone Due to Recent Bhuj Earthquake

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ESTIMATE THE MAGNITUDE AND NATURE OF DISTRESS THE VARIOUS STRUCTURES HAVE UNDERGONE DUE TO RECENT BHUJ EARTHQUAKE

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ABSTRACT

On January 26, 2001 one of the most destructive earthquakes ever to strike India occurred in Gujarat. More than 13,000 lives were lost in this earthquake. Several civil engineering sections have undergone moderate to severe distress. In this paper two cases of one port at Adani and a salt factory which has undergone severe distress has been covered.

INTRODUCTION

Bhuj (Gujarat, India), experienced considerable distress due to the earthquake, which stuck on the January 26th, 2001 at 08.46.54.8 hours. Several civil engineering structures underwent distress. It was found that the epicentre of this earthquake was at latitude 23.45 degrees north and longitude 70.34 degrees east near Bhuj town in Kachchh district of Gujarat. The earthquake was of the magnitude 7.8 on the Richter scale due to which, several towns namely Bhuj, Anjaar, Bachau, Sukhpur were completely flattened. All these towns are east of Bhuj.

Analysis of the preliminary recorded seismograms from several countries of the Bhuj earthquake indicates that the magnitudes are Ms 7.9 (NEIC), Mw 7.5 (NEIC), Mw 7.6 (HRV), and Mb 6.9 (IMD). The focal point is placed at a shallow depth of 18.2 km and indicates predominantly reverse thrust along a moderately dipping east-west tending plane (strike 249, dip 29 and rake 78.7) with slight slip component. The maximum slip amounts to 6.2 m at near hypocentre. The seismic moment, $M_o = 2.6 \times 10^{20}$ Nm, source duration 20 s. A small event was followed by a large one about 2 seconds later. Subsequently more than 150 after shocks were felt in duration of one month.

Areas several hundred kilometres from the epicentre experienced severe earthquake. As the epicentre was near the sea, several areas in the vicinity of the epicentre experienced liquefaction. Adani port and Bachau, which are on marine sedimentary deposits are located around 60 to 80 km from the epicentre, and in both the cases the sea is within a radius of 5 km. Typical borelog in this area is presented in Figure 1. The author had an opportunity to deeply study the case of distress and recommend remedial measures. This paper presents the case histories of two sites one for Adani port near Mundra where the entire area was mapped just after the earthquake and other a salt factory near Bhachau where liquefaction analysis was carried out.

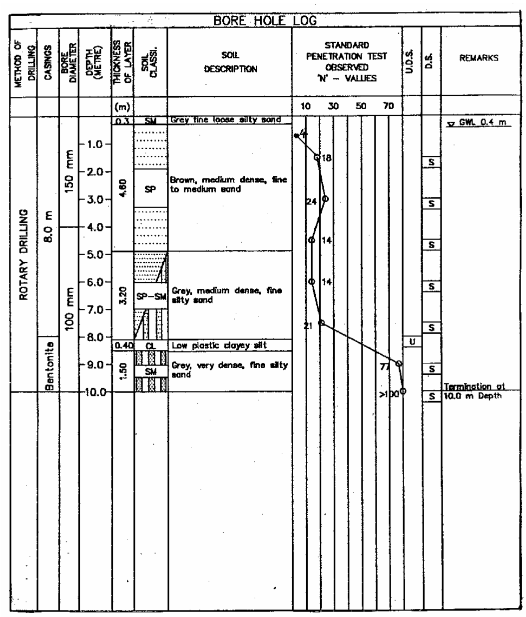

Fig. 1 Typical borehole in Adani Port area

CASE 1

Adani port, is located around 70 km south of Bhuj is a port town in Gujarat. Due to the earthquake, the port complex experienced distress in various structures. These included bund area, go-downs, open stack yard, railway yard etc.

SUB-SURFACE

The sub-surface comprises of layer of blackish grey silty clay having thickness of around 5 m. The N value of this zone is less than 3. Stiffer strata up to large depths follow this. There appears presence of large longitudinal cracks in several areas such as the rock-fill embankment, open go-downs, and the receiving and dispatch yard of the railways.

From the sub-surface investigation carried out before and after the earthquake indicate that, the N valee at a deoth of 1 m dropped from 5 to 0 before and just after the earthquake. Table 1 shows the variation of N value with depth before and just after the earthquake.

Table 1. Variation of N and ϕ value with depth

Depth	Before earthquake		Just after earthquake	
	N	ϕ	N	ϕ
1	5	0.5429	0	0.0
2	10	0.5890	0	0.0
3	14	0.6248	2	0.4663
4	18	0.6619	4	0.5429
7	30	0.7399	15	0.6494
9	35	0.7813	35	0.7002
10	38		45	

Bund Area

The sub-surface profile of the bund area comprises of 30 cm of loose fine silty sand, which is followed by 4.5 m to 5 m thick brown dense, medium to fine sand. The penetration value in this area varies between 3 at an depth of around 1.0 m to as high as 24 at a depth of 3.5 m and then again reduces to 14 an a depth of 4.75 m. This layer is followed by Grey medium dense fine silty sand. The thickness of this layer is around 3 m. The penetration value in this layer varies between 12 and 17.

Beyond this layer Grey very dense fine silty sand is observed. The penetration value in this layer starts from 21 and goes as high as 77.

The brown dense, medium to fine sand comprises of nearly 98 % of sand and 2 % silt and clay. The liquid limit of this material is of the order of 18 % and is non-plastic.

This layer is followed by grey medium dense fine silty sand with sand as high as 92 percent and silt and clay 8 %. This material has liquid limit of 18 % and is non-plastic in nature. The specific gravity of this layer is 2.63.

Grey very dense fine silty sand is observed subsequently. In this case the sand content has come down to around 75 % and silt and sand content around 25 %. The liquid limit is 20 and this layer is also non-plastic.

Tank Area

In this area mainly only two horizons are observed. The top five meters comprises of blackish grey silty clay. The penetration value of this layer varies between 0 and 17. The specific gravity of this layer is 2.60 and it consists of around 20 % sand, 50 % silt and 30 % clay. The liquid limit obtained is 54 % and the plastic limit is 25 %. The field dry density is 1.5 g/cm^3, and field moisture content of 33.33%. The shear strength parameter c is 0.23 kg/cm^2 and 17 degrees. The initial void ratio is 0.75 with C_c around 0.31.

This is followed by Blackish silty poorly graded sand mixed with seashells. The N value in this layer increases from 7 at a depth of 9 m to as high as 38 at a depth of 20 m. The specific gravity of this layer is 2.67 with around 85 % sand, 1 % silt and remaining clay. The liquid limit of this soil is around 18 and is non-plastic.

Open Go-down Area

The open go-down area covers: Open storage for sulphur, open storage enclosures 1 to 7, FRM go-down, new FRM go-down, closed go-downs 1 to 9, proposed area for silos, 16500 ton storage area with conveyor connectivity, 25000 ton storage area with conveyor connectivity, DOC open go-down and DOC covered go-down, etc.

The subsurface in this area comprises of, soft yellowish brown to light grey fine to medium grained sandy silt with kankars and pebbles up to a depth of meter or so. This is followed by very soft bluish grey clay having penetration value of the order of 2. This layer is encountered up to a depth of 3 to 3.5 m. Subsequent to this Soft bluish grey silt is seen up to a depth of 7 m. The penetration value of this layer varies between 3 and 13.Medium dense to very dense bluish grey, well-graded sand is encountered subsequently, which extends up to a depth of nearly 35 m. The penetration value of this layer varies from 17 to as high as 116 at a depth of 35 m.

PRESENT STATE OF DISTRESS

It was observed that several locations in the project area have under gone distress.

The entire project area can be divided in four zones namely: The bund area, the liquid container tank enclosures, the open go-down and dry cargo area and the receiving and dispatch railway yard area.

Bund Area

The bund area is the zone parallel to the conveyor belt connecting the service area and the jetty as depicted in Figure 2. The length of this approach bund approximately 700 m. It comprises of rock-fill embankment whose height varies from around 2 m to as high as 7 m. The top width of the approach bund is 12.5 m and the side slope is 1 in 1.5. As the height of the embankment increases, burm is also provided to account for stability.

Crack is observed on the bund. It is seen that the cracks originate at pedestal 63 at chainage 44.7 m and go up to pedestal 76 at chainage 174.7 m. Subsequently no crack is observed between chainage 174.7 m and 344.7. Then again the crack is observed from pedestal 93 at chainage 344.7 m till pedestal 111 at chainage 524.7 m. The average thickness of the crack is around 6 cm.

Liquid Container Tank Enclosure

As per the information made available by the competent authorities of Adani port, they have carried out a detailed survey of the tank area after the earthquake. It is concluded that all the tanks are in plumb hence indicating that they have not tilted. Levels taken on the top of the pile raft indicates that the pile rafts have neither lifted nor settled and the raft is intact after the earthquake. The settlements observed between the pedestals and the pile rafts are only due to the settlement of the surrounding soil.

Fig. 2. Bund area parallel to the conveyer belt

Open Stacking Yard and Dry Cargo Area

The open stacking yard and dry cargo area covers the major area comprising of: Open storage for sulphur, open storage enclosures 1 to 7, FRM go-down, new FRM go-down, closed go-downs 1 to 9, proposed area for silos, 16500 ton storage area with conveyor connectivity, 25000 ton storage area with conveyor connectivity, DOC open go-down and DOC covered go-down, etc. The entire area has undergone settlement and at several places water has oozed out on the surface and fine sand is spread over the entire area which can be clearly seen in Figure 3

Open Storage For Sulphur

The area covered in this zone is approximately 35850 sq m. The average reduced level of the area at the end of the construction was 6.80 m while the reduced level as on March 5, 2001 is 6.597 m. The average settlements in various areas are presented in Table 2. This indicating that the average settlement in this area is of the order of 0.2035 m.

Fig. 3. Open stacking yard and dry cargo area

Table 2. Average settlements in open storage for sulphur

S. No.	Area	Average settlement
1	Open storage area 1	0.1793 m
2	Open storage area 2	0.206 m
3	Open storage area 3	0.234 m
4	Open storage area 4	0.033 m
5	Open storage area 5	0.1735 m
6	Open storage area 6	0.186 m
7	Open storage area 7	0.1 m
8	FRM area	0.091 m
9	Closed go-downs 1 to 7	0.0829 m
10	DOC open and closed go-down and open storage area	0.131 m

Receive and Dispatch Railway Yard

The railway embankment starts at chainage 0.0 at Adipur near Gandhidham to chainage 63400 m at the container yard. The embankment is constructed over the virgin land by compacting layers of soil using vibratory rollers so as to achieve at least 98% modified proctor density.

The embankment is 6.85 m wide and the height of the embankment is dependent on the final formation level, which varies between 1 meter and 6 maters. It is seen that from chainage 0.0 to chainage 54000 m the entire embankment is intact and no distress of any kind is observed.

The first sight of distress is observed between chainage 54670 m to 54850 m. In this area the side slopes of the embankment has shifted and bulging failure is observed. Similarly at chainage 54990 the pile heads on which the pipes were placed have displaced in the eastward direction.

Major distress is observed on the railway embankment when the embankment crosses the road. Here 15 cm wide longitudinal cracks are seen over the entire width of the embankment as seen in Figure 4. The wing was has displaced more than 15 cm away from the concrete structure.

Fig. 4. Longitudinal crack over the length of the embankment

Fig. 5. Wet hole on February 11, 2001 from which water and silt had oozed out

On the top of the embankment at several places silt is oozed out from the embankment and spread over 3 m to 4 m. The diameter of these holes is as high as 10 cm as seen in Figure 5. The height of the water jet, which came out of the embankment, was around a meter or metre and a half. The depth of these cracks was as high as 2 m to 2.5 m.

INSTRUMENTATION

To understand the in-situ characteristics of the sub-soil it is proposed to carry out extensive instrumentation in the field along the bund. The proposed instruments comprise of:

Vibrating wire piezometers to measure the pore pressures at a depth of 1 m, 3 m and 6 m from the ground surface. These may be placed 5 m away from one another. Magnetic settlement markers or equivalent to measure the settlements at a depth of 1 m, 3 m and 6 m from the ground surface. Horizontal displacement markers to measure the horizontal shift of the bund, and inclinometers, to measure the slip of the bund. Surface settlement markers.

SUMMARY AND CONCLUSIONS

From the entire observations it is observed that it is necessary to evaluate the liquefaction depth and also monitor the entire area. Detailed investigation and instrumentation programme was prepared and given to the port authorities. This will help to understand the various engineering properties of the soil. These will include: Grain-size distribution of soil, Density of the deposit, vibration characteristics, location drainage and dimensions of deposit, magnitude and nature of superimposed loads, method of soil formation, period under sustained load, previous strain history and entrapped air

From the above data one is in a position to determine the depth and nature of liquefaction.

Similarly by installing the various instruments one can determine the nature of development of pore pressures, movement of the embankments and so on.

Case 2

LOCATION OF FACTORY

The salt factory is located at Bhachau in Kachchh District of Gujarat, which is sixty km off Bhuj and one hundred km from Rajkot. To get an overall picture of the entire site it is proposed to carry out 9 boreholes. These boreholes are marked between BH-1 through BH-9.

BORE HOLES

To find the solutions for restoring the structures in most economical and efficient manner, it is very essential to understand the engineering properties of the sub-soil. For this it was proposed to carry out nine boreholes scattered over the entire factory area.

All the tests shall be carries as per the procedures laid down by the Bureau of Indian Standards.

Presentation of Boring Data

At the salt factory unit at Bhachau in Gujarat, in all nine bore holes were carried out. All these boreholes were extended up to around 15 m depth. Water table was observed at a depth of 1.5 meter to 2.0 meter. In all these boreholes mainly 3 horizons are observed while in case of boreholes 1and 4, four horizons are observed.

Horizon 1. Horizon 1 is filled up ground with assorted material composition. This extends up to 1.5 m. depth.

Horizon 2. Horizon 2 is Yellowish loose fine sand with silt and clay. It extends from 1.5m to (6.5-8.0) m. The bulk density observed is 1.85g/cc and the moisture content is 12% -16 %. The ranges of Attereberg limits are: liquid limit 25%-45%, plastic limit 10%-20, and plasticity index 10-24.The gradation of the soil shows gravel 3%-11%, sand 40%-50%, silt 10%-27%, and clay22%-28%. The SPT values are in the range of 9-15.

Horizon 3. Horizon 3 is Yellowish medium plastic very stiff clay with silt and fine sand. It extends from 6.5-8.0 m to 10.5-15 m. The bulk density observed is 1.9 g/cc and the moisture content is 18%. The ranges of Attereberg limits are: liquid limit 60%-72%, plastic limit 9%-16%, and plasticity index 42%–45%. The gradation of the soil shows gravel 3%-2%, sand 9%-16%, silt 36%-40%, and clay 45%-52%. The SPT values are in the range of 21 to 35.

Horizon 4. Horizon 4 is Yellowish medium plastic very stiff clay with silt. This horizon is found to be at times below the horizon 2 as in case of boreholes 3, 4, 6 etc., it extends from (6.5-8.0) m to (12-15) m. The bulk density observed is 1.9g/cc and the moisture content is 12%-16%. The ranges of Attereberg limits are: liquid limit 34 %-38 %, plastic limit 14%-25%, and plasticity index 20%-22%. The gradation of the soil shows gravel 3%-4%, sand 17%-30%, silt 5%-27%, and clay 42%-36%. The SPT values are in the range of 21 - 35.

COMPILATION OF FIELD AND LABORATORY DATA

To understand the nature of strata an attempt is made to tabulate the various engineering properties of the soil obtained from various boreholes with depth. Typical results from the laboratory teats are presented in Table 3.

Consolidation Test Data

The consolidation test values carried out are presented in Table 4. From the above table it is very clear that between 1.5 m and 6.0 m: The plasticity index lies between 5.5 and 20 and only in one case is 24, the liquid limit of the soil lies between 20 % and 30%, the clay fraction content of the soil is between 20 % and 27 %.

Variation of penetration value with depth is presented in Figure 6. From the penetration values observed in the field it is seen that the N value lies between 7 and 20 between depths 1.5 m and 6 m hence we can infer that the soil is loose to medium dense kind of material. It is observed on the site that liquefaction of the soil has taken place. This is confirmed from the fact that sand boils are observed on various locations on the factory site. Hence it is observed that due to liquefaction the soil has become loose. Hence we may go in for higher factor of safety.

Table 3. Summery of engineering properties of soil

Bore Hole	**Depth in m**	**Gravel**	**Sand**	**Silt**	**Clay**	**LL**	**PL**	**PI**
BH-4	1.5	11	42.3	19	27.7	26.5	14.7	11.8
BH-5	1.5	4	46.7	26.8	22.5	28	10.6	17.4
BH-6	1.5	9.9	49.3	25.9	14.9	24.5	15	9.5
BH-7	1.5	11	48.8	16.3	23.9	26.5	15.5	11
BH-9	1.5	3.5	47.5	26.6	22.4	30	14.3	15.7
BH-1	3	3.4	40.7	27.8	28.1	30	9.4	20.6
BH-2	3	9.9	45.1	17.2	27.83	25	16.1	8.9
BH-3	3	3.7	49.4	19	27.8	40	15.9	24.1
BH-7	3	13	63.3	9.6	14.1	21	15.5	5.5
BH-8	3	0	50.9	29	20.1	32	17.2	14.8
BH-2	4.5	14	54.5	11.2	20.3	23.5	14.7	8.8
BH-4	7.5	7	30.3	26.9	35.8	46.5	20.6	25.9
BH-4	7.5	1.4	6.7	39.4	52.5	76	34	42
BH-6	7.5	4	31	41.3	23.7	44.5	22	22.5
BH-8	7.5	3.4	41.7	24.8	30.1	29	13.4	15.6
BH-4	9	1.4	9.3	36.3	53	72.5	25	47.5
BH-7	9	3	20.2	36.5	40.4	45	14.7	30.3
BH-8	9	4.3	50	27	18.7	35	26.9	8.1
BH-2	10.5	2.9	15.8	36.7	44.6	59	14	45
BH-3	10.5	4.5	17.2	35.4	42.9	38	15.9	22.1
BH-4	13.5	3.4	16.2	32.7	47.8	60.5	20.6	39.9
BH-6	13.5	1.4	17.6	36.6	44.4	43.5	15	28.5

It may be kept in mind that the water table is below 1.5 m in the month of June. In January due to the dynamic forces and the wave action the water table had risen up to the top, which can be clearly seen, from the sand boils on the ground surface. If detailed calculations are carried out this statement can be proved. Hence the point of tan able or not does not arise. One has to carry out a detailed analysis as stated earlier. Even the

IS 1893 specifies that the soil is susceptible to liquefaction if N value is less than 15.

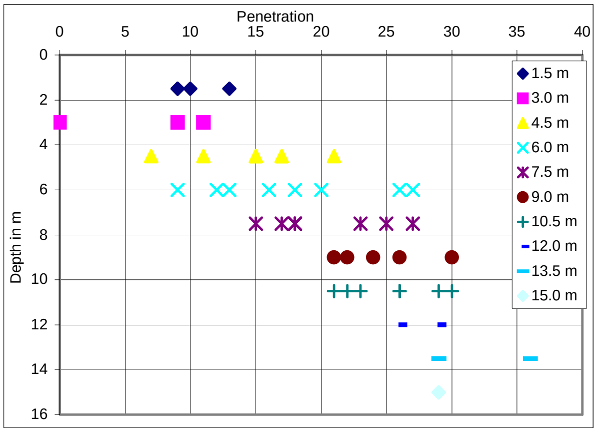

Fig. 6. Variation of penetration value with depth

Fig. 7 Location from where the salt and water oozed out at salt factory at Bachau

LIQUEFACTION ANALYSIS

Based on the field and the laboratory data, liquefaction analysis is carried out. The detailed calculations for evaluation of liquefaction potential are presented in Table 5 and 6. From the calculations it is evident that liquefaction has taken place. It is observed that the depth of liquefaction is up to 5 m from the ground surface.

Fig. 8. Structure of salt factory after the earthquake

The photographs, in Figure 7 which were taken just after the earthquake on the January 26th, 2001, also clearly indicate that the liquefaction has occurred at the site.

Figure 8 shows the structure of the salt factory, which clearly shows that the chimney is out of plumb and the entire structure has undergone severe damage.

At several places the partition walls have collapsed and the surrounding soil and flooring has undergone settlements.

Table 4. Consolidation characteristics of soil at salt factory

		B. H. 1		**B. H. 3**		**B. H. 7**		**B. H. 8**	
S. No.	**Pressure in kg/cm^2**	**C_v in m^2/year**	**C_c**	**C_v in m^2/year**	**C_c**	**C_v in m^2/year**	**C_c**	**C_v in m^2/year**	**C_c**
1	0.2	15.73	0.26	2.90	0.27	2.90	0.41	3.61	0.31
2	0.5	12.81		3.33		0.89		8.0	
3	1.0	8.75		2.90		2.90		4.41	
4	2.0	2.90		1.95		1.95		4.84	
5	4.0	2.22		8.75		2.90		8.41	
6	8.0	2.53		2.90		2.53		10.24	

Fig. 9. Settlement of the surrounding flooring and the entire flooring of the stacking go-down is cracked

CONCLUSIONS

From the field photographs after the earthquake, the investigation carried out after the earthquake and the theoretical analysis carried out, it is clear that the area surrounding the salt factory at Bachau has undergone liquefaction.

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Table 5. Evaluation of liquefaction potential

Evaluation of τ_o											Evaluation of τ_{av}			
Depth in m	Depth in Feet	Density in t/ m^3	Density in t/ft^3	Stress in t/m^2	Stress in t/ft^2	C_N= 0.77* $\log_{10}$ (20/stress)	Penetration value N	Corrected penetration value N'	Ratio of shear stress and normal stress	τ_o	a_{max}/g	* r_d from graph	$\tau\alpha\varpi$	Whether Liquefaction will occur or not
1.000	3.281	1.800	0.056	1.800	0.184	1.567	9.000	14.105	0.163	0.030	0.300	1.000	0.036	Yes
2.000	6.562	1.800	0.056	3.600	0.369	1.335	10.000	13.355	0.150	0.55	0.300	0.990	0.071	Yes
3.000	9.843	1.825	0.057	5.475	0.561	1.195	10.000	11.953	0.125	0.070	0.300	0.980	0.107	Yes
4.000	13.123	1.850	0.058	7.400	0.758	1.095	14.000	15.323	0.175	0.133	0.300	0.976	0.144	Yes
5.000	16.404	1.875	0.059	9.375	0.960	1.015	15.000	15.231	0.175	0.168	0.300	0.966	0.181	Yes
6.000	19.685	1.900	0.059	11.400	1.167	0.950	17.000	16.150	0.188	0.219	0.300	0.960	0.219	No
7.000	22.966	1.900	0.059	13.300	1.362	0.898	20.000	17.969	0.200	0.272	0.300	0.950	0.252	No

Table 6. Evaluation of liquefaction potential based on N value

Depth in m	***Depth in Feet***	**Density in t/ m^3**	**Density in t/ft^3**	**Stress in t/m^2**	**Stress in t/ft^2**	**a_{max}/g**	**r_d**	$\tau_{\alpha\varpi}$	**Determination of N_c**	**C_r**	σ_{dc}/σ_a	**e_{max}**	**e_{min}**	**e**	**D_r**	**Stress causing liquefaction τ**	**Whether Liquefaction will occur or not**
1.000	3.281	1.800	0.056	1.800	0.184	0.300	1.000	0.036	22.000	0.640	0.205	0.51	0.420	0.449	67.778	0.010	**Yes**
2.000	6.562	1.800	0.056	3.600	0.369	0.300	0.990	0.071	22.000	0.600	0.205	0.54	0.430	0.443	88.182	0.012	**Yes**
3.000	9.843	1.825	0.057	5.475	0.561	0.300	0.980	0.107	22.000	0.578	0.205	0.52	0.450	0.483	52.857	0.007	**Yes**
4.000	13.123	1.850	0.058	7.400	0.758	0.300	0.976	0.144	22.000	0.680	0.205	0.58	0.410	0.446	78.824	0.013	**Yes**
5.000	16.404	1.875	0.059	9.375	0.960	0.300	0.966	0.181	22.000	0.600	0.205	0.59	0.480	0.527	57.273	0.008	**Yes**
6.000	19.685	1.900	0.059	11.400	1.167	0.300	0.960	0.219	22.000	0.600	0.205	0.59	0.480	0.527	57.273	0.008	**Yes**
7.000	22.966	1.900	0.059	13.300	1.362	0.300	0.950	0.252	22.000	0.600	0.205	0.59	0.480	0.527	57.273	0.008	**Yes**