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Attenuation of Ground Vibration on Saturated Silt Clay and Rock Bases

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SYNOPSIS: By actual measuring and theory analysis , this paper obtains the saturated water massdensity and shear modulus of saturated soil , and also the major factor affecting near source attenuation by the mteration of soil skeleton and water , the later also being the major factor affecting far source attenuation. The paper inquires into the affect of the depth of underground water on the wave propagation. For rock base, as the wave velocity of rock body wave is high and the body wave attenuation much faster than the surface wave does,so the near source attenuated generally faster than the soil surface does. The elastic property of rock is better than the soil , althouth its self-excited vibration frequency is high, the damping of the material is small. So the far source attenuated much slower than soil does.The paper also inquires into the effect of the covering layer of rock surface, the tread of rock structure, and the ditch on the attenuation of vibration wave. The geometry attenuation factor and soil attenuation factor in the formula of attenuation calculation are also recommended in the paper.

INTRODUCTION

Saturated silt clay and rock bases are two of those which are much different from common soil and are less studied on their property of ground vibration. The former has the character of high water content, large void ratio, low compression modulus and low load carrying capacity. The rock base of the latter is just opposite.It has better elastic property and is generally hard to compress except the decayed rock, and so has the high load carrying capacity . For these much differed base soils, their maximum influencing factors on wave motion are wave velocity and material damping . For the wave motion of saturated soil, if it is considered as the saturated porous medium , according to Biots assumption that fluid body is a compressible liquid and can flow freely through the soil pore space, when the wave propagates in saturated soil at common frequency, the skeleton frame and water will vibrate at the same time . For the rock half space divided into small plots owing to the joint, Li Guo-Ping used the "micro-pole elastic theory" and considered the wave motion of the rock ground as the "micro-pole wave" to study. In practical engineering, how to predict the attenuation of ground vibration of this kind bases in a simple and clear way is a very important subject in engineering decision making . It involves the problems of industry environment in the city transformation and the development of industry zone (machinery, traffic, and engineering of construction) . Some research literatures often used the Bonitz's plane wave equation to conform the actual attenuation curve . In this case, the most important parameter r - radius of wave source, which is the distance from vibration source to the point at known amplitude, is the variable varying from less than one meter to nearly a hundred meters , and so this equation is difficult to be properly applied though it seems practical . This paper has made some addendum to the geometrical attenuation and soil material attenuation factorys in the attenuation calculation equation according to dozen groups of actually measured data on saturated silt clay and rock bases. Examples show that the calculation result is very consistent with the field measured curve.

WAVE MOTION CHARACTERISTIC OF SATURATED SILT CLAY AND ROCK BASE.

It has been measured that the Vs (S-wave-velocity) in saturated soil is indentical to that in nonsaturated natural soil , but the mass density , because of the action of water buoyancy force, is smaller than that of nonsaturated natural soil, and the shear modulus is reduced accordingly. For silty soil, it may be reduced 40%-60% (Pan). And the geometry damping of wave source is, at same time, reduced and the amplitude of wave source raised.The material damping of saturated soil is also reduced compared with latter. The filed-measured wave velocity of rock base is usually that the body wave velocity is high and surface wave velocity is low and approaching to that of common soil. This is because the μ and ρ of rock is much larger than that of soil, and the rock surface has been affected by weathering fissure and covering layer,making its surface wave velocity much lower than that of body wave.

The vibration frequency of saturated silty soil and rock bases is correlated with distance and wave source energy. For large energy wave source on saturated silt , the ground 200m away from wave source still has the wave source frequency, and for small energy wave source , the ground several dozends of meters beyond the wave source will has different frequency from wave source. For example, the ground frequency of staturated silt soil in Shanghai, under the wave motion of common machine vibration energy , is about 8.5-

10.5Hz. When wave source frequency is higher than this value, the ground frequency , beyond certaindistance , will be decreased and then stablized within the above range . And when the wave sourence frequency is lower than this value , it will raised to this frequency range beyond certain distance . Figure 1a illustrates this phenomenon by actual measureing period . For the vibration frequency of rock base , near source frequency is usually higher than that of far source. Figure 2 shows that the wave source frequency of micro weathering granite is 16Hz ; and at the place 102m away from the source the frequency on the surface of covering layer of nearly 6m deep power soil is 8 Hz , this being possibly the frequency of the covering layer ; and at the far rock surface 163 m beyond the surface the frequency becomes 28 Hz , but it is only 15 Hz at the soil surface of 300m thick covering layer at the same point , correlating wave source frequency . The actual measuring period in figure 1b expresses this characteristic of rock base.

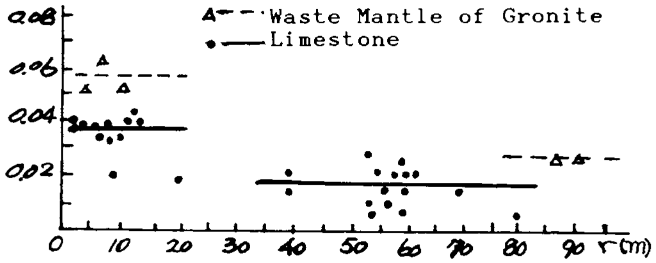

Fig.1 a) Relationship of Ground Maximum Amplitude and Period on Rock Base (With Covering Layer.Forging Hamme)

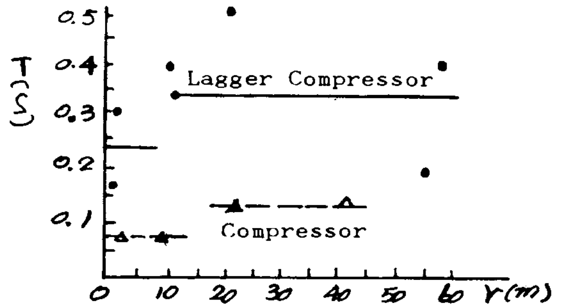

Fig.1 b) Relationship of Ground Maximum Amplitude andPeriod on Saturaled Silt Clay

PROPAGATION AND ATTENUATION OF GROUND VIBRATION OF SATURATED SILT AND ROCK BASES.

Geometrical attenuation . Under the action of machinery wave source , the ground vibration attenuation of saturated silt soil at both near source and far source is all slower than that of nonsaturated soil which has the same porosity ratio and other common properties . This is caused by its variation of velocity and shear modulus after saturated with water . For rock base , because the near source body wave has big specific gravity and attenuates quickly , so the geometrical attenuation is quickened accordingl . The geometry damping of wave source can be expressed approximately as follow : (Yan,Wang)

$$Cz=\frac{r_0}{a_0}\sqrt{\mu_p\rho}\,[-f2/(f^2 1+f^2 2)] \qquad (1)$$

Where r_0 -radius of wave source ; $a_0=\omega r_0/v_S$; ω - circular frequency ; v_S -S-wave velocity ; $\mu\rho=\rho v_S^2$ -soil shear modulus ; f1 , f2-- dynami placement founction . It can be seem from equation (1) that when the μ_p and ρ of saturate soil decrease and the Vs decrease only ver little , the geometrical radiation damping o wave source Cz will decrease accordingly. So th geometrical attenuation of the energy radiate to wave source verge will also decreased . Fo rock base , when the Vs under wave sourc increase , its Cz value will increase as th first power of Vs , and the geometrical attenuation of the energy radiated to wave source verg will also increase quickly . Away from the wav source verge , the body wave will attenuate a r^{-2} . This has reflected the characteristic tha for near source , the saturated silt soil attenuates more slowly than the common soil does, an rock base attenuates more quickly. The geometrical attenuation of the attenuation formula in < design specification for dynamic machine foundation >> (Yang Xian-Jian 1981) is the value inside the radical sign of the equation below This values expresses the geomotrical attenuation of energy radiation by body wave in the form of half sphere and surface wave in the form of annulation .

$$A_r=A_0\sqrt{\frac{r_0}{r}\left(1-\zeta_d\left(1-\frac{r_0}{r}\right)\right)}\;\exp(-\alpha_0 f_0(r-r_0)) \qquad (2)$$

Where A_0 -amplitude of wave source ; f_0 -frequency of wave source ; ζd-geometrical attenuatior factor ; α_0-energy absorption factor caused by soil materical attenuation . The relationship between ζd and r_0 statistically calculatec according to actual measuring material is giver in table 1 .

Soil material attenuation . The dynamic characteristic of saturated soil is also related with certain frequency range . This relationship can be expressed approximately as $\beta=\omega^3/(V_p^2 c)$. Where : Vp - plane wave velocity of ground ; c - soil coefficient of consolidation . When β is small , the frequency is low and ground fluctuates slowly , and saturated water is of low-flowing . Under some energy, the consolidation and loading may be accomplished simultaneously . When β is large , the freqiency is high and ground fluctuates quickly , and there is undrained phenomenon within a period . So the medium is just like a kind of almost incompressible elastic material . For saturated soil , the soil material attenuation of far source and the geometrical attenuation of near source all comform to this relationship . Further more , for the material damping of which the far source saturated water and soil skeleton will move together , and soil and liquid will act commonly , the effect of β relationship will play the main rule . For the common machine vibration frequency, the exponent term in formula (2) $a_0=(1.25\sim1.35)\times10^{-3}$s/m -- the water table stablizes in the position of less than 1m to soil surface ; $a_0=1.85\times10^{-3}$s/m -- when water table is 2.5~3.5m to soil surface , i.e. the depth of undergroundwater is larger than 3m, the ground vibration attenuation is consistant with that of nonsaturated soil of the same kind. The above a_0 values also indicate that the atteuation of saturated soil is slower than that of onsaturated soil of the same kind. For the very small energy wave source generated by machanical type vibration exciter, the Shanghai's saturated soil which has high water table gives $a_0=1.5\times10^{-3}$ s/m . The rock base is related with the thickness of covering layer . When the thickness is less than 2.5m , the shale , limestone $a_0=(0.4\sim0.5)\times10^{-3}$s/m ; sandston $a_0=(0.6\sim0.8)\times10^{-3}$s/m .

Effect of underground water depth of saturated soil and the covering layer thickness of rock surface . The wave motion under the interaction of saturated soil skeleton and fluid is related to its permeability . The less the permeability is , the smaller its related c value is , and then the β value will increase , the resistance to seepage flow , under the wave motion of same frequency , will increase , drainage consolidation will decrease , and as the result, a_0 value will decrease (attenuation decrease) . When there is the same porosity ratio and no underground water , the a_0 value will increase and the soil with larger porosity ratio will quicken to attenuate . The effect of underground water depth on β value is related with wave length. Usually when underground water is deeper than 2.5m , the actually measured far source a_0 is approximately equal to that of nonsaturated soil of the same kind . For the higher frequency wave source , when underground water is deeper than 2m , the a_0 value will be approximately equal to that of the latter . This is coincided with the theory that the surface wave length of saturated soil is about 10m and the maximam effect of plane wave will be at over 1/3 wave length . The frequency of covering layer on the rock surface decreases as the increase of covering layer thickness and then stabilizes in the range of the natural vibration frequency of covering layer . If the thickness of covering layer continues to increase , it may maintain wave source frequency under the common wave source energy . The frequency of some covering layer can be estimated by the following equation : $f_s=V_s/4H$, here H is the thickness of covering layer . For example , in figure 2 , Vs=186m/s , at the position of r=82~127m ,the average thickness is 5m , it is calculated that fs=9.3 Hz , consistant with actually measured value fs=8~11 Hz obtained at three points of the above mensioned place . And this frequency , being lower than that of wave source 16Hz , is the covering layer frequency . The damping ratio of rock and covering layer surface is smaller than that of common soil . For example , at the position of r=22m to 3T forging hammer, the damping ratio of limestone surface is 1/6 of that of 300~500 mm thick covering layer surface , and the damping ratio of covering layer surface is about 1/2 of that of common soil . On the other hand , the vibration number of times of rock surface is 5.5 times of that of soil surface and the vibration time is less than 0.2 s for soil surface and is 0.4~0.77 s for rock surface . This is the main reason that although the vibration frequency of rock base is very high , its far source vibration wave attenuates more slowly than the common soil surface does . The effect thickness of covering layer is about 6m for near source and about 1.5~2.5m for far source . It can be considered as common soil type if the thickness exceeds these values . This thickness is also approching to 1/3 wave length . Although the surface wave velocity of covering layer surface is higher than that of common soil surface , the ground frequency is high and so the surface wave length is shorter . For near source the embedment and geometrical attenuation factor of wave source are consderes and so it effect depth is larger than that of far source .

TABLE 1. Geometrical Attenuation Factor ξ_d

r_0 \ soil	Equivelent Radius of Wave Source r (m)			
	≤ 0.5	1	2	3
Rock	0.90-0.99	0.85-0.90	0.80-0.85	0.75-0.80
Saturated soil	0.85-0.99	0.65-0.70	0.50-0.55	0.45-0.50
Common soil	0.85-0.99	0.70	0.60	0.55

r_0 \ soil	4	5	6	≥7
Rock	0.70-0.75	0.65-0.70	0.60-0.65	0.40-0.50
Saturated soil	0.35-0.40	0.30-0.35	0.25-0.30	0.20-0.10
Common soil	0.45	0.40	0.35	0.25-0.15

Note : (1). r_0 is mean value and interpolation method can be used to evaluate ξ_d value .

(2). For saturated silt soil , when the depth of underground water is equal to or less than 1m , smaller ξ_d value is used , and when it is 1.5~2m , larger ξ_d value is used , and when it is more than 2.5m , the ξ_d value for common soil is used .

(3). For rock , when the thickness of covering layer of rock surface is within 2.5 m , larger ξ_d value is used , and when it is over 2.5m , smaller ξ_d value is used , and when it is over 6m , the ξ_d value for common soil is used .

Rock construction strike and surface fluctuation effect . The wave propagation on rock base has obvious directivity . There is a much difference between vibration wave attenuation along the rock strike and the perpendicular to it (figure 3) .For the latter case , the velocity of the filler between the rock stratum is much lower than that of rock stratum itself , then the isolated layer for vibration is formed , so , its geometrical attenuation will obviously quicken compared with the former case . Because the material damping of rock stratum is about the same , so for far surface , the atteuatiuon of both the cases has almost no difference . The scale of rock surface fluctuation is related to wave length . For the wave source of low frequency (below 50 Hz) , when the Vp of rock surface is about 2000 m/s , there exists the ditch of 1~2 m deep on the rock surface and in the position 10 m away from the ditch , the ground amplitude may be amplified by over 200% . We can often find this amplification phenomenon in the actually measured material obtained from the rock surface having covering layer . When the ditch dimension is larger than $0.2\lambda_p$ (λ_p -- body wave length) ,no amplitude is amplified beyond the ditch , but in the edge and bottom of the ditch , wave scattering will take place and then the togographic and geomorphic effect will be formed .

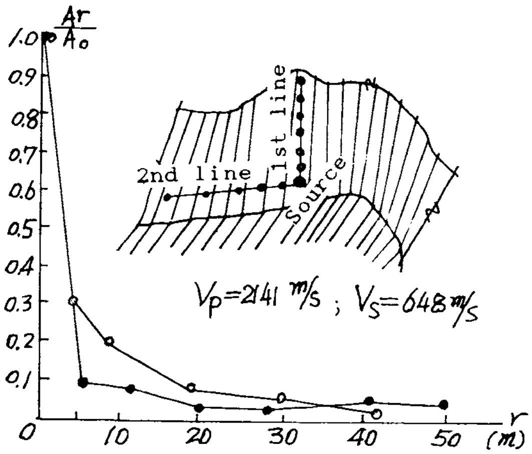

Fig.3 Relationship of Ground Vibnation of Rock Base on Rock Strike

EXAMPLE

Figure 4 is the attenuation curve of actually measured ground vibration of saturated soil base and that calculated according to formula (2), in which when the wave source is pile foundation , the amplitude "bulge" phenomenon will take place at the distance corresponding to the marked height of pile bottom . This is caused by the superposition of the surface wave formed at this place owing to body wave of pile bottom on the original surface wave . Figure 5 is the correlation curve of ground vibration of rock base and the theory calculation . It can be seem from the figure , the calculation result according to formula (2) coincides very well with actually measured curve .

CONCLUSION

The effect of saturated silty soil and rock bases on ground wave motion is mainly caused by wave velocity and self-characteristic of rock and soil . The permeability and floating weight of saturated soil and rock tread and ditch (though its dimension is not large) will all affect the geometrical attenuation and material attenuation.

The maximum effect of underground watre depth of saturated silt and covering layer thickness and rock surface on ground wave motion is within the range of 1/3 surface wave length for far source, and the geometrical attenuation of near source is also mainly caused by wave velocity .

The wave sources involved in this paper are all at rock surface . If the wave source is at soil surface , the wave motion property of rock base has some difference from the former case , This difference is related to soil layer and covering layer of rock surface under the wave source. For example , under the foundation of 16 T forging hammer , a cushion of 250 mm thick graded sand cobble and 100 mm thick bitumen and sand grout is set up, and under the cushion, the reinforced concrete base-plate is anchored to rock. In this condition , the base-plate and hammer foundation form the vibration isolation system , so the amplitude of base-plate is much reduced compare with that of foundation . The wave source amplitude should be that of base-plate . Some reference takes its foundation amplitude as wav source amplitude , and then obtains a differen curve from the near source attenuation of commo rock base . On another limestone surface , ther is the powder soil of about 10 m thick and th 5 T die-forging hammer foundation on the covering layer of powder soil with cobble. Its groun vibration attenuation has no difference fro that of common soil .

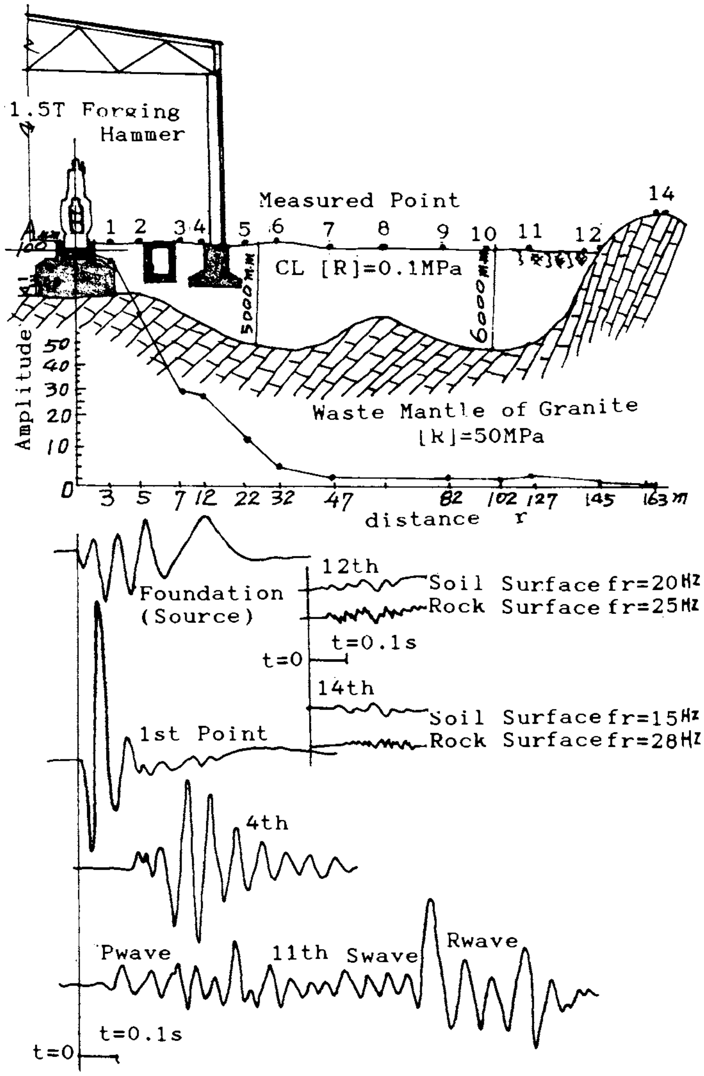

Fig.2 Effect of Covering Layer on Gronitic Base

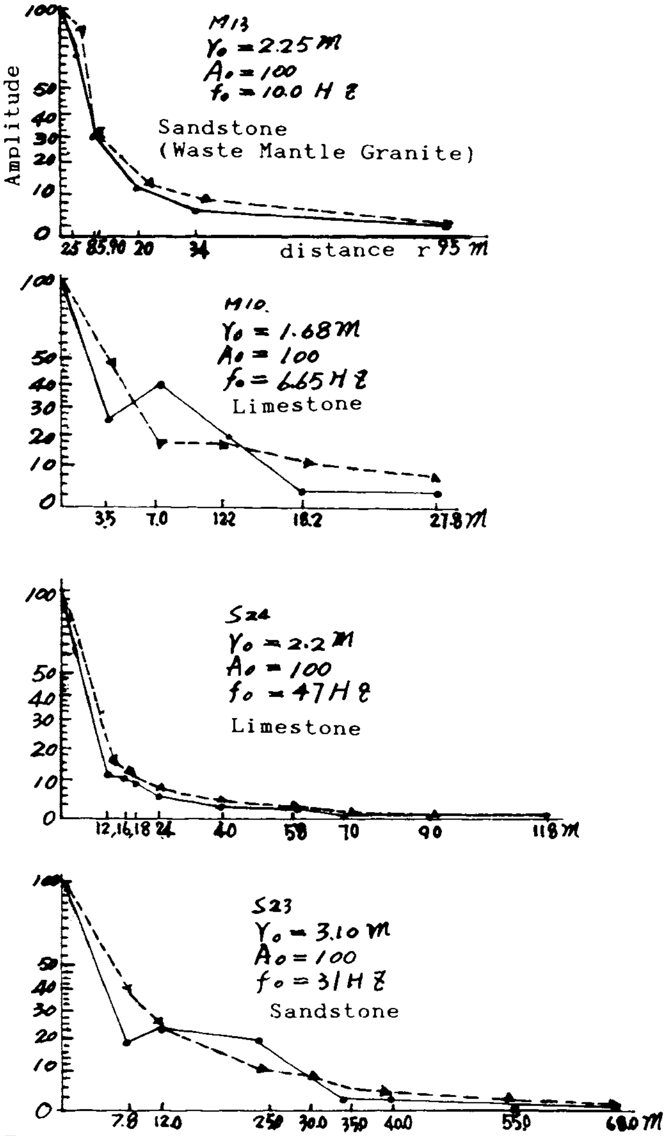

Fig.5 Attenuate Curve of Rock Bases

●—— Measured Line △---Calculated Line

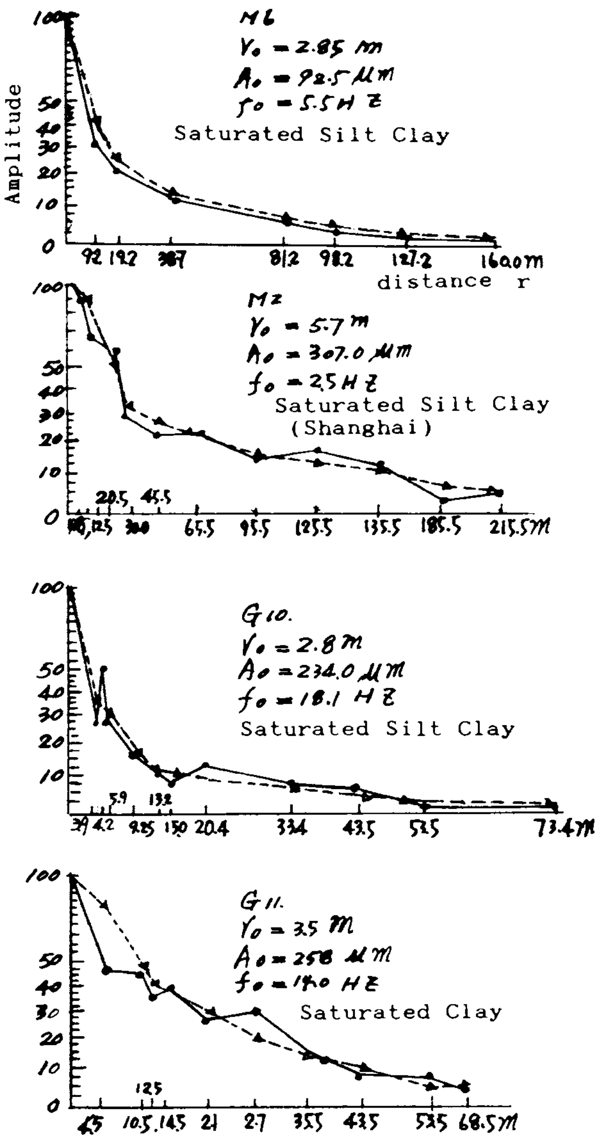

Fig.4 Attenuate Curve of Saturated Silt Bases

●—— Measured Line △---Calculated Line

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