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Influence of Water Content on Elastic Properties of Expansive Soil

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Abstract. Shrink-swell characteristics of expansive soils cause differential settlement beneath foundations, and the volume shift in the soil can cause serious structural damage, the elastic properties of the soil are one of the elements that are affected at the same time. These properties are also required for studying such soils using FEM modeling or software techniques. In the present investigation, an attempt has been made to establish a correlation between the elastic properties of expansive soil and the variation in its water content , which may be used directly for analytical studies. The stress-strain curve obtained from the triaxial test is used to compute the initial tangent modulus and secant modulus, while the Poisson's ratio of soil is derived using unconfined compression tests at various strain values. The findings were compared to those of earlier studies. The R^2 (strength of association) value was well above 0.92 for the obtained correlation for water content and poisson's ratio. The values of tangent and secant modulus were observed to increase until the optimum moisture content was exceeded by 2-4 percent, after which they decreased.

Keywords: Expansive Soil, Elastic Properties, Young's Modulus, Poisson's Ratio, Correlation.

1 Introduction

Expansive soil makes up one-fifth of India's land area. This sort of soil, which becomes soft when wet or saturated, is frequently referred to as "black cotton soil." Structures may suffer damage from changes in soil volume. On the other hand, the features of the soil involved in each project are needed for the numerical study. It is hard to get these features for expansive soil because it is always changing due to changes in its water content. Modulus of elasticity and Poisson's ratio are among the most crucial aspects of the analysis.

Jambu (1961) provided the expression for Young's Modulus (1), which was later modified by Lade (1988) by incorporating shear into the equation (2). They concentrated mostly on reinforced soil Behaviour, which is defined by the modular ratio, which is the modulus of soil to the modulus of reinforcement. Modified Equation given is:-

$$Es = KPa\left(\frac{\sigma}{Pa}\right)^{n} \quad ....(1)$$

where σ is lateral confining pressure and p_a is atmospheric pressure. Parameters K and n are specific to a soil.

Vanapalli and Oh (2010) provided a semi-empirical model for forecasting the fluctuation of unsaturated soil modulus of elasticity utilizing the soil water characteristic curve and the modulus of elasticity under saturated conditions, as well as unsaturated soil carrying capacity and shear strength. The stress versus displacement curves for many model footings on saturated soil were used to build this model. They utilized two fitting parameters in the given equation given below,

$$Eunsat = Esat[1 + \alpha \frac{(\mathrm{Ua}-\mathrm{Uw})}{\frac{\mathrm{Pa}}{101.3}} S^{\beta}] \ldots (2)$$

where, $u_a - u_w$ is the matric suction of soil, P_a is atmospheric pressure in kPa,S is degree of saturation of soil.The fitting parameter α can estimated based on a relationship proposed between inverse of α and the plasticity index. It is seen that 1/α increases non- linearly with increasing plasticity index.

In the experimental study by Duncan and Chang (1970), elastic moduli of soil were determined from the stress strain curves of triaxial tests during the shearing of saturated/unsaturated compacted specimens under different confining stresses. The stress strain data of triaxial shear test can be represented mathematically by a hyperbola having the form,

$$\frac{\mathrm{s}}{(\sigma 1-\sigma 3)} = \frac{1}{\mathrm{E}} + \frac{\mathrm{s}}{(\sigma 1-\sigma 3)\mathrm{u}} \ldots .(3)$$

where E is modulus of elasticity, ε is Stain, $\sigma 1$ and $\sigma 3$ are principal stresses in triaxial test setup.

Work by Lu and Kaya (2014) presents a simple power law to characterize the relationship of soil elasticity to volumetric water content. Uniaxial compression tests are performed on compacted soils with changing water content. Young's modulus tests the power-law relationship. The proposed power law fits well with existing models, but is simpler because the other models employ matric suction and volumetric water content as independent variables and entail additional fitting factors. Measure elastic moduli at dry, wet (almost saturated), and intermediate points. The proposed power law describes changes in soil elastic moduli under variable saturation. A study by Adem and Vanapalli (2014) proposes a dimensionless model to predict the elasticity of unsaturated expanding soils. This study applies the dimensional analysis (DA) using conventional and suction-controlled triaxial test findings for three compacted expanding soils. The state of hydration of soil (matrix suction and degree of saturation), the amount of compaction and confinement (initial void ratio and confining stress) are dimensionless criteria for determining the soil modulus of elasticity. Several non-dimensional parameters are employed with Buckingham pie theorem. Research by Sharma (2017) implemented Artificial Neural Network (ANN) to calculate the modulus of elasticity. Gravel, sand, fines, liquid limit, Plastic Limit, unit weight, and specific gravity are inputs in the ANN model, while Modulus of Elasticity is the output. The accuracy of this ANN model was compared to a regression analysis model, and it was found to be more dependable for predicting soil modulus of elasticity. The Modulus of Elasticity Based Method (MEBM) is presented for predicting the heave/shrinkage of natural expansive soils over time by Adem (2015). The proposed MEBM uses a simplified constitutive relationship to estimate vertical soil motions over time in terms of matric suction and modulus of elasticity. MEBM was tested for five case studies and predicts soil movements well in all cases. MEBM predicts vertical movements of natural expanding soils under lightly loaded constructions. Dong et al. (2014) studied shear strength in China's black cotton region. The goal was to determine gully erosion in gully walls where shear characteristics are important. Six kinds of soil were sampled: surface soils from four land uses and 30 cm and 60 cm deep. At 10 levels of water content, cohesion and internal friction angle were measured. The relationship between water content, cohesiveness, and internal friction was observed and modelled. Another study by Batiste (2014) was done to identify the clay stiffness characteristics and derive an empirical relationship with respect to the equations developed by earlier researchers. A comparison was done between the idealized and actual stress strain Behavior of soil. Many more studies [11-14] were done in the area by the researchers.

Soil elastic characteristics are widely utilized to estimate settlement from static loads the elastic modulus of soil is a soil characteristic used to measure soil stiffness. Elasticity properties of soil are also employed for numerical modelling utilizing the finite element method and software such as PLAXIS, ANSYS, GEOSLOPE, VADOSE/W, and many others. In the current study, to investigate the effect of water content on the modulus of elasticity and shear parameters various geotechnical tests has been performed and properties of soil were determined. Triaxial compression test were conducted with three different cell pressures at different samples prepared for variation of water content. Cohesion and angle of internal friction was calculated by using the Mohr’s envelope. Modulus of elasticity of soil was estimated by plotting the stress - strain curve of the soil and an attempt has been made to correlate the same with water content.

2 Experimental Program

2.1 Material Used

The soil used for this study is black cotton which is taken from different sites in Bhopal City. Two samples were collected as Black cotton (BC) soil-1 MANIT campus and black cotton (BC) soil 2 taken from Ratibad, which was 12 km away from MANIT.

Table 1:- Properties of the Soil Sapmles

Characterstic	BC Soil-1	BC Soil 2	Code
Liquid limit	53.66	55.62	IS: 2720 (Part 5)
Plastic limit	24.84	29.34	-
Plasticity index	28.82%	26.28%	-
Specific gravity	2.69	2.67	IS: 2720 (Part 3)
Differential Free Swell (DFS)	52%	55.6%	IS: 2720 (Part 40)
Field Density	20.45 kN/m^2	20.67 kN/m^2	IS: 2728 (Part 29)
Max. Dry Density (MDD)	15.2 kN/m^2	15 kN/m^2	IS: 2728 (Part 8)
Optimum Moisture Content (OMC)	17%	18.40%	-

Samples were collected and tested to obtain the basic soil properties shown in Table 1. Using the obtained values, soil has been classified based on the plasticity chart shown in Fig. 1. It is clear that both the soils lies above the A-line and have liquid limit greater than 50%, so both the soils have been classified as CH, i.e., Highly compressible clay.

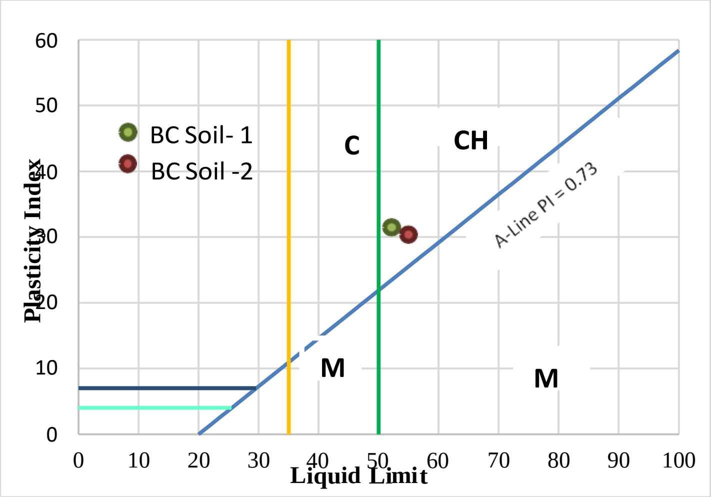

Fig. 1. Casagrande plasticity chart

Fig. 2. Failure of soil sample

The elasticity and shear characteristics of expansive soil are the primary areas of investigation in the current work. Using the appropriate tests allowed for the determination of the numerous geotechnical qualities that the soil possesses. The outcomes of a triaxial test are utilized in the computation of the shear parameters of soil. The value of the initial tangent and secant modulus of elasticity can be determined from the slope of the stress vs. strain graph produced by the triaxial test. In order to acquire different values of elastic and shear parameters for comparison, the water content was increased by 2 percent for each test. This was done in order to alter the moisture level of the soil and obtain different results. The failure samples from the tests are shown in Fig.2.

3 Result and Discussion

3.1 Shear Parameters of Soil

Calculating the shear parameters requires a triaxial test, which corresponds to an optimal moisture level of 17 percent, with an additional increment of 2 percent each time for fluctuation in moisture content. The Mohr circle is created for each of the three distinct cell pressures, and a line tangent to each of the circles is then used to calculate the Mohr-Columb failure envelope. The value of cohesion and the slope of the same are both determined by the failure envelope's intercept, given that the angle of internal friction shown in Table 2 is adhered to.

The deviator stress vs. axial strain plot is drawn with the help of triaxial test data at various moisture contents. The three different plots are drawn with respect to the cell pressure applied on the soil,Fig 3 represents this variation for the sample at Optimum Moisture content.. The slope of the stress – strain curve gives us the value of the modulus of elasticity. The value of slope until the graph behaves as a straight line, treated as the initial tangent modulus (Eo) whereas the line connecting the origin with the point of failure is indicated by the secant modulus (Es).

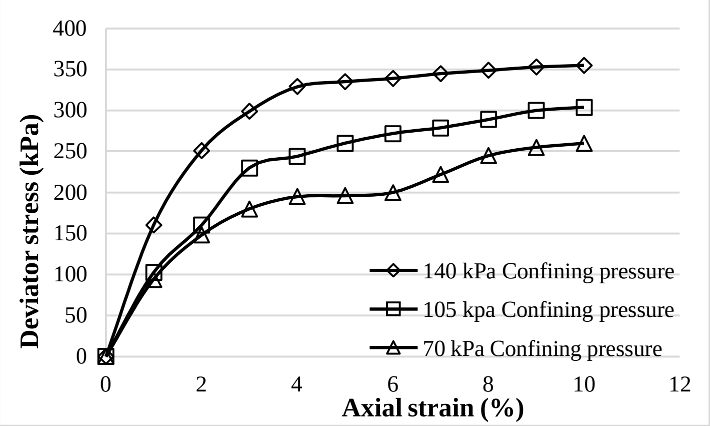

Fig. 3. Stress vs Strain at Optimum Moisture Content

3.2 Variation of Test Results With Water Content

According to the findings of this study, the value of cohesiveness rises alongside an increase in the percentage of water present; nevertheless, once a specific value is reached, the percentage of water present causes a decline in cohesion. This finding can be understood if one takes into account the fact that soil cohesiveness can be attributed to the compaction of the soil particles, electrostatic and electromagnetic forces, as well as capillary potential. All of these characteristics gain intensity as the percentage of water in the soil increases, up to a point that is unique to each type of soil. If the soil moisture is allowed to rise above this threshold, the distance between the particles will grow, which will result in a reduction in the electrostatic, electromagnetic, and capillary potential.

Table 2: - Test Results of BC-1 for variation of water content

Moisture Content	Cohesion (kPa)	Angle of Internal Friction	Initial tangent modulus (E_o) (kPa)			Secant Modulus (E_s) (kPa)			Poisson's ratio (μ)
17	117	11.12°	10465	9942	12147	4466	3862	5378	0.473
19	146	8.75°	9939	7481	7850	5197	5116	5806	0.475
21	132	4.91°	4641	2358	5232	4114	3935	4269	0.479
23	118.4	3.37°	5756	7850	7852	3633	3024	3429	0.489
25	90	1.93°	6802	7857	9942	2586	2457	3027	0.469

Table 3: - Test Results of BC-2 for variation of water content

Moisture Content	Cohesion (kPa)	Angle of Internal Friction	Initial tangent modulus (E_o) (kPa)			Secant Modulus (E_s) (kPa)			Poisson's ratio (μ)
19	122	5.02°	5495	8373	7850	3133	3380	3587	0.474
21	170	4.24°	3134	2221	2615	4133	4864	6124	0.476
23	114.5	2.7°	2465	1569	2129	2468	2548	3548	0.485
25	112	2.01°	3401	3925	4710	2414	2342	2656	0.492
27	94	1.72°	4331	6803	6829	2162	2021	2202	0..496

The values of the angle of internal friction kept on decreasing as the water content was increased (Table 1,2). This is because as the water content is increased, the water between the particles forms a layer of water film that plays an important role in lubrication. This is why the values of the angle of internal friction kept on decreasing. During the shearing process, the angle of internal friction will decrease if there is an excessive amount of water present. Because the clay particle is smaller in size, it has a better capacity for retaining water, and the water content of the variable interval is low; as a result, the moisture content has a greater influence on the angle of internal friction. The values of the initial tangent modulus at a certain cell pressure drop up to a particular water content, but then they start to increase again as the water content continues to rise.

The value of Secant modulus at a particular cell pressure increases up to OMC + 2% but decreases as further the water content is increased.

3.3 Elastic Properties

The values of Initial Tangent Modulus drop as the water content increases up to an addition of 4-5 percent in OMC, but after that, very little increment is seen in the values. That could be because the initially the load is taken by the abundant water in the soil system, a similar pattern has been observed for all the cases of cell pressure. Figures 4-5 provide a visual representation of the change that occurs in the Secant modulus. It is obvious that as the water content rises, the secant modulus also rises, but only up to the point where the water content is 5–6 % greater than the OMC. After that point, the Secant Modulus begins to decrease as the water content continues to rise for a given cell pressure.

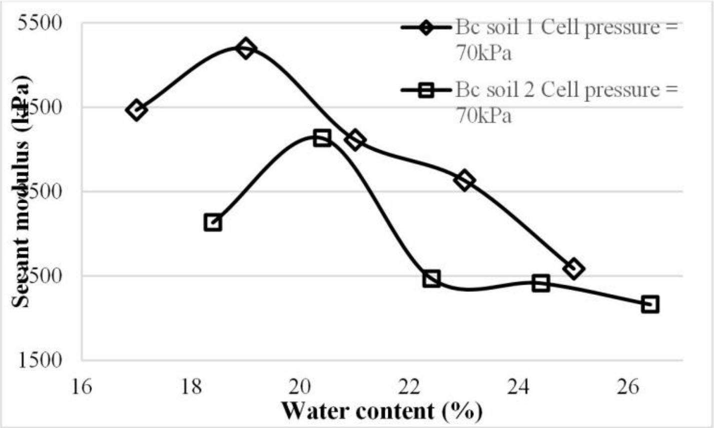

Fig. 4. Variation of Secant modulus (E_s) with water content at Cell pressure 70kPa

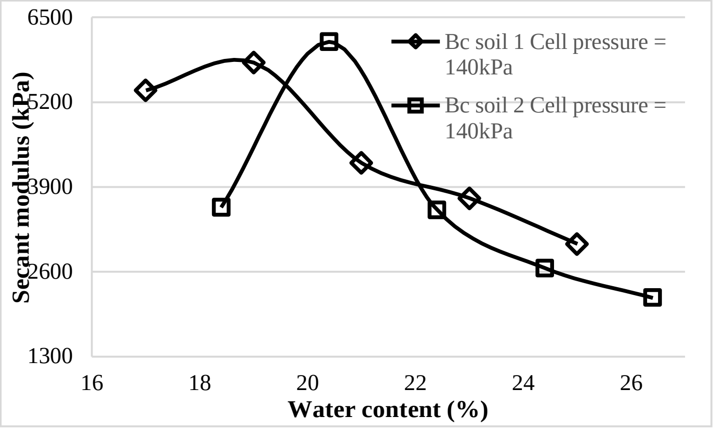

Fig. 5. Variation of Secant modulus (E_s) with water content at Cell pressure 140kPa

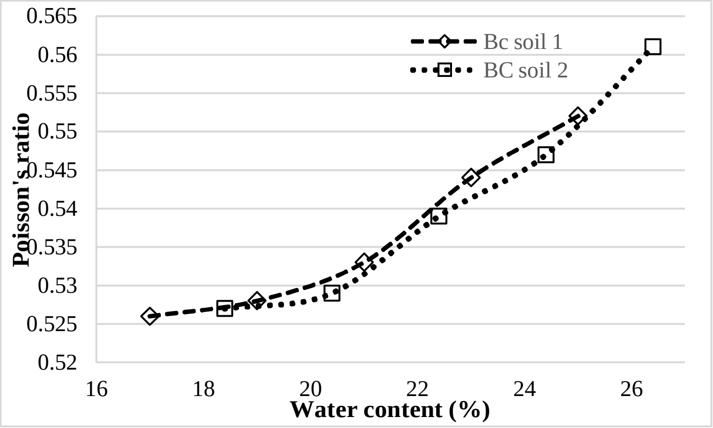

Fig. 6. Variation of Poisson’s ratio with water content

When more water is added to the soil sample for any of the two soils under consideration, the soil's Poisson ratio rises. For both soil samples, the poisson's ratio measures 0.52 at the optimum moisture level. As the water content is added, the values continue to rise. This is evident from Fig. 6. This explains why the stress originating from one axis would cause the body on the other axis to distort by a greater percentage when water was added to the soil system.

4 Correlation

With moisture content, a correlation between shear characteristics and elastic modulus has been developed. The derivation is made using the laboratory data that has been calculated above. For each parameter, the correlation is calculated using linear regression and presented in Fig. 7-11.

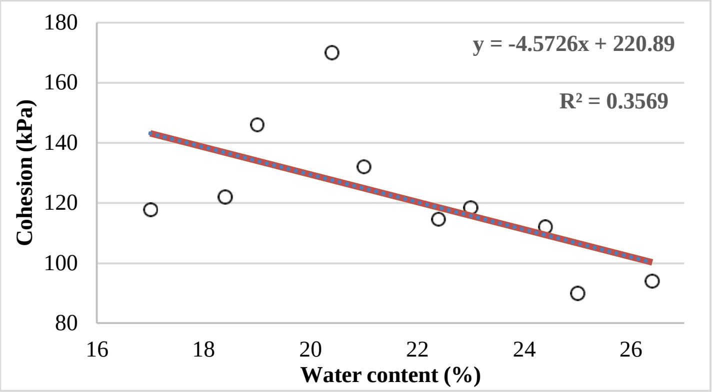

Fig. 7. Cohesion vs water content

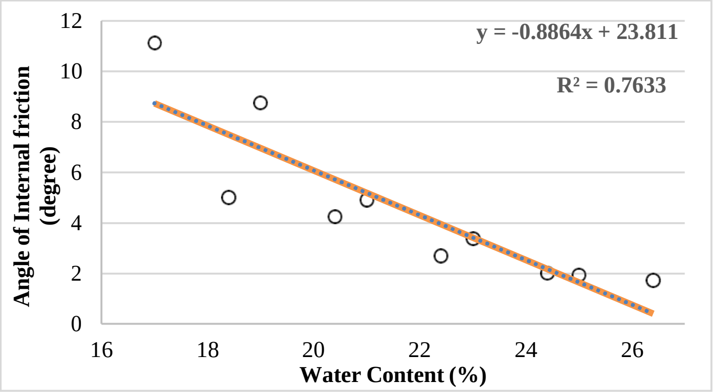

Fig. 8. Angle of internal friction vs water content

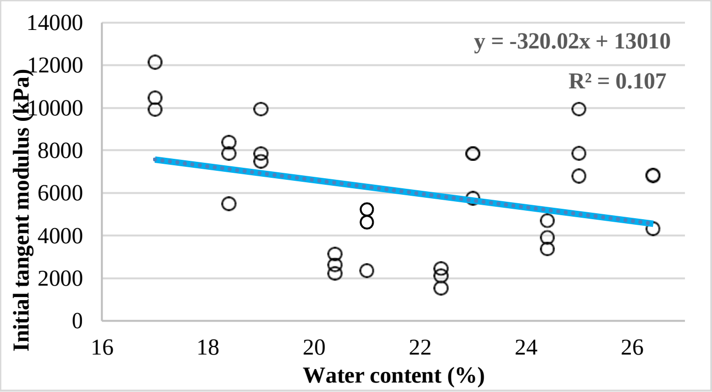

Fig. 9. Initial tangent modulus (E_o) vs water content

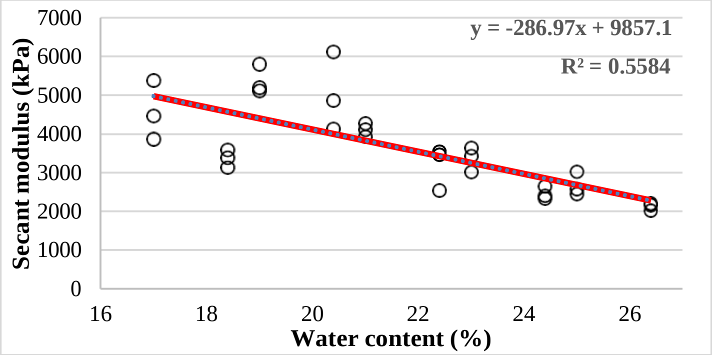

Fig. 10. Secant modulus (E_s) vs water content

The initial tangent modulus vs. water content equation that was obtained had a very low value for the coefficient of regression R2, and the instance where the Poisson's ratio was 0.93 had the highest value. Similarly, the result is close to 0.77, which is also somewhat favorable when the angle of internal friction and moisture content are taken into account. The obtained equations are also shown in the relevant figures.

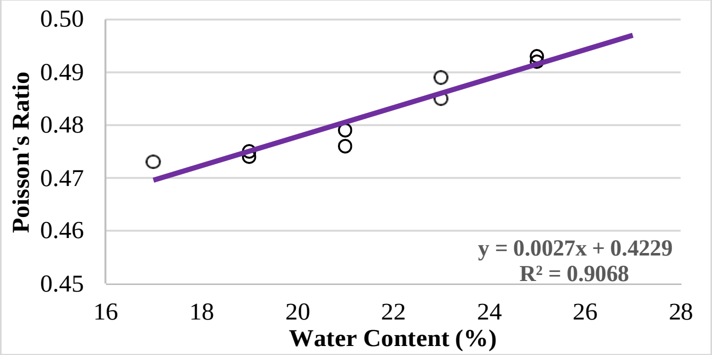

Fig. 11. Poisson's ratio vs water content

5 Conclusion

This research aims to gain a better understanding of the effect of water content on the elasticity and shear characteristics of expansive soil. Modulus of elasticity and shear parameters are computed utilizing the triaxial test, whilst Poisson's ratio is computed utilizing the unconfined compression test. The following inferences are drawn from the findings.

- The values of cohesion increase and attains the maximum value and further decrease as the water content is increased. The water content can be termed as the critical water content If the soil moisture exceeds this limit, the separation between particles increases causing the electrostatic, electromagnetic, capillary potential to decrease and cohesion decreases.

- The values of angle of internal friction keep on decreasing on increasing the water content it is because as we increase the water content the water between the particles forms a layer of water film which plays which plays an important role in lubrication. Also, the clay particle is smaller in size, and with good water retention much water so, on increasing the water content the angle of internal friction decreases.
- The values of Initial tangent modulus (E_o) at a cell pressure decreases up to certain water content but increases further as the moisture content is increased.
- The values of Secant modulus at a specific cell pressure rise up to 4%–5% over the optimum moisture content, but they decrease as the water content rises further.
- On increasing the water content, it is seen that the values of Poisson's ratio increases. Since the soil is cemented due to capillarity and adsorption as the saturation continuously decreases, Poisson's ratio starts to increase as the internal stress increases. The derived equation $y = 0.0027x + 0.4229$ has the R^2 value of 0.9068.

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