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Comparison of Mat Foundation Design Using Rigid Method and SAFE Program

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ABSTRACT

Reinforced concrete mat foundations are popular foundation type commonly used in high rise buildings. These foundation systems may be designed and analyzed as either rigid bodies or as flexible plates supported by an elastic foundation. This research is to compare the similarities and differences of both rigid and flexible methods through the use of mat foundation modelling. A symmetrically loaded mat foundation models with equal column spacing were analyzed and designed using the conventional rigid method procedure and then the same models were reanalyzed and redesigned as flexible bodies using SAFE v12.2 computer program. Consequently among design strips, it has been numerically found that the one way shears achieved by the rigid method are more than those of SAFE program with the considerable fluctuations of their amounts. Thicker mat is required to check punching shear according to SAFE program in comparison with that of the rigid method. Furthermore, the flexural moments gained by SAFE program are more around columns and lesser at strip mid spans comparing to those reached by the rigid method. It can be concluded that there are some differences of the results between both methods. This paper recommends to cautiously use the application program with deeply understanding of input design parameters such as modulus of subgrade soil reaction.

Keywords: SAFE Program, Rigid Method, Flexural Moment, Punching Shear.

1. INTRODUCTION

The mat or raft foundation is a continuous footing supporting a group of columns and walls in several lines in each direction. ACI 336 [1] described that mat foundations cover the entire area under a structure or an area of at least 75 percent of total area within the outer limits of the structure.

A reinforced concrete mat foundation is a common structural type of foundation systems used on erratic or relatively weak supporting soil subjected to more substantial loads from the building where a large number of spread footings would be required. In addition, it may be more economical to use a mat foundation when spread footings cover more than one-half the foundation area [1]. Mat foundations are generally used with soil that has a low bearing capacity but mats, often with piles, are also essential to resist uplift hydraulic pressure from those places where water table above the foundation levels [2].

Bowles [2]; Das [3]; Klemencic, et al [4] schematically show several types of mat foundations used currently including flat plate, flat plate thickened under columns, beams and slab, flat plates with pedestals, slab with basement walls as a part of the mat where the walls act as stiffeners for the mat, and mats placed directly above piles. The flat plate type of mat foundations is to be considered in this paper.

The structural analysis of mat foundations can be carried out by two conventional methods: the conventional rigid method and the approximate flexible method as exemplified by Das [3]. Alternatively, the mat is divided into a number of finite elements and three general finite element formulations may also be used involving finite difference, finite grid and finite element methods [1, 2]. One of disadvantages of finite element formulations is computationally intensive but computers and available programs make the use of finite element methods economical and rapid.

The conventional rigid method is characterized by its simplicity and ease in execution. In contrast, the resultant of column loads does not coincide with the resultant of soil pressure under the individual design strips, which leads to violation of the static equilibrium equations. Therefore, ACI 336 [1] restricts the use of conventional rigid method and suggests that mat foundation may be designed by considering design strips both ways and treating the mat as a rigid body where column spacing is less than 1.75 divided by a coefficient (β) or the mat is very thick, and variation of column loads and spacing is not over 20%.

$$\beta = \sqrt[4]{\frac{\beta_1 Ks}{4E_F I_F}} \dots\dots\dots\dots\dots\dots\dots..(1)$$

Where Ks , E_F, I_F and $\beta_1$modulus of soil subgrade, modulus of foundation material, moment of inertia of strip design beam and strip width, respectively.

Although a variety of commercial computer program is available relating to the analysis and design of mat foundations, the authors avoid to provide recommendations for any specific analysis program [1, 2, 4]. Therefore, before structural designers use a computer software, they need to validate the reliability of the software in terms of both safety and economic aspects.

This study is to compare and show the similarities and differences of both rigid and finite element methods through the use of mat foundation modelling. Mat Foundation models are analyzed and designed as flat plate rigid body using the conventional rigid method and then SAFE v12 based on finite element method is applied to analyze and design the equivalent models. The main focus is to investigate the results obtained from both methods.

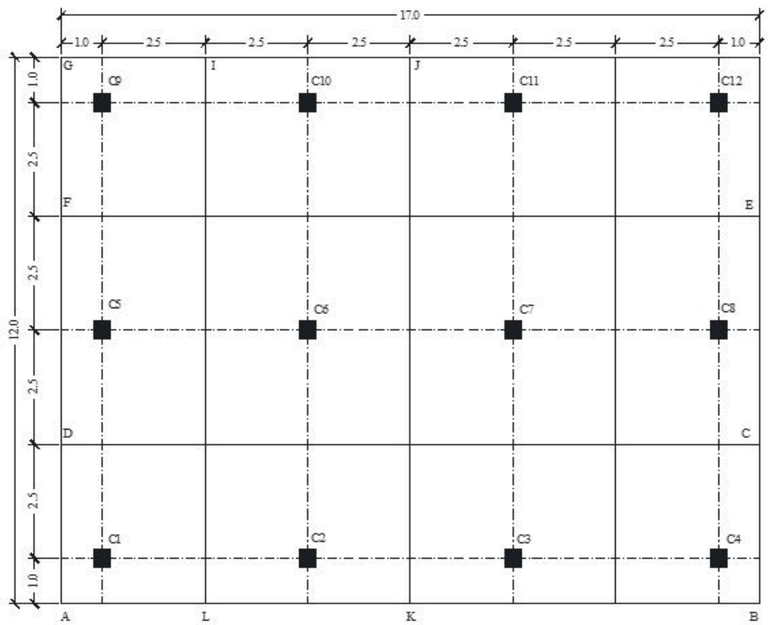
The design of mat foundations has long been recognized as a problem in soil-structure interactions that designers have tried to simplify by designing mats that can be classified as rigid bodies [4]. Soil-structure interactions, and soil properties are beyond the scope of this research.

2. MAT FOUNDATION MODELLING AND DESIGN PARAMETERS

To design a mat foundation, the geotechnical engineer will need to provide structural engineer with those design parameters relating to supporting soil properties such as allowable bearing capacity (q_a), anticipated settlements (δ), and modulus of subgrade reaction (Ks). On the other hand, structural engineer will choose any design parameters belonging to construction materials used in the mat. As a result, the appropriate design of any foundation system prerequisites the clear and effective communication between the structural and geotechnical engineers [4]. The process of the mat foundation modelling of this research includes the following steps:

2.1 PLAN AND LOADING OF THE MAT FOUNDATION MODEL

Prestigious foundation design textbooks often illustrates conventional rigid method to escape from disequilibrium of the applied loads and soil pressure either by selecting symmetrically-loaded strips and using uniform soil pressure to reduce the eccentricity to zero and avoid serious errors [5]. Therefore, a symmetrically loaded mat foundation models were taken into account with 17m by 12m in plan as shown in Figure 1.



Note; All dimensions are in meters

FIGURE 1. Plan of the mat foundation models

The mat carried the 3 by 2 bays concrete frame with equal column spacing (5m) in both directions (x, y), and cross sections of columns are 0.4m x 0.4m. Realistic dead and live loads were estimated for a 10 story public building frame based on ASCE 7-10 [6] and transferred to the mat using tributary area as presented in Table 1. This paper only considers static gravity loads (service dead and live loads) coming from the superstructure with linear elastic behavior analysis.

TABLE 1.
Column dead and live loads

Columns	Dead load (KN)	Live Load (KN)
Corner	800	600
Edge	1000	900
Interior	1400	1200

2.2 DESIGN PARAMETERS

The mat foundation consists of normal concrete mix and steel reinforcements. The design and analysis of the mat foundation models needs the property of the construction materials and consequently the appropriate design parameters were fixed for both rigid method and SAFE program as shown in Table 2.

Specified compressive strength of concrete ($f_{c'}$) was set to 30 MPa using cylinder specimens and specified yield strength of reinforcement (f_y) was indicated as 400MPa. The allowable bearing capacity of soil (q_a) used in the conventional method was 120 KN/m^2. The three parameters plays a significant role in the analysis and design process.

TABLE 2.
Design parameters

Parameter	Notation	Value
Specified yield strength of reinforcement, MPa,	f_y	400
Specified compressive strength of concrete at 28 days, MPa,	$f_{c'}$	30
Modulus of elasticity of reinforcement, MPa,	Es	200,000
Modulus of elasticity of concrete, MPa,	Ec	26667
Concrete weight, kg/m^3	w_c	2356
Poisson ratio, concrete	μ	0.2
Allowable bearing capacity, KN/m^2	q_a	120
Modulus subgrade reaction of soil, KN/m^3	Ks	14,400
Bearing capacity factor of safety	FS	3
Mat cover (top, bottom, sides), mm	C	50
Steel Diameter, mm	ϕ	25

Many empirical equations for predicting the modulus of elasticity for concrete as a function of compressive strength can be found in the literature. According to ACI 318-08 [7], Section 8.5, modulus of elasticity (Ec) for concrete has been found using Eq. (2). Modulus of elasticity (Es) for nonprestressed reinforcement shall be allowed to be taken as 200,000 MPa.

$$Ec = w_c^{1.5}\, 0.043\sqrt{f_{c'}} \ldots\ldots\ldots\ldots\ldots (2a)$$

$$Ec = 4700\sqrt{f_{c'}} \ldots\ldots\ldots\ldots\ldots\ldots\ldots (2b)$$

Where; w_c is normal weight of concrete in kg/m3, $f_{c'}$ and Ec are in MPa.

By default SAFE uses modulus of elasticity (26667MPa) for 30MPa strength of the concrete. This value is in the range of the results achieved by equations 2a and 2b.

2.3 MODULUS OF SUBGRADE REACTION

Soil is naturally non-linear, anisotropic and heterogeneous and its deformation is depended on the stresses that are applied to soil [8]. Hence, for design of the structure supported by soil, instead of modeling the subsoil in all its complexity and various properties, it can be replaced by a simpler parameter called a modulus of subgrade reaction (Ks). Accordingly, this parameter plays an important role in all three discrete element methods given for analysis and design of mat foundation [2]. To design reinforced concrete mat foundations in SAFE Program, Ks is a fundamental parameter that needs to be defined instead of (q_a).

It has been frequently stated that Winkler [9] firstly proposed a model to calculate Ks that was considered as a linear ratio between the contact pressures (q_a) and the associated vertical displacement (δ), it has units of force per unit volume (MN/m3).

$$Ks = \frac{q_a}{\delta} \ldots\ldots\ldots\ldots\ldots (3)$$

Reference to the literature review given by Naeini et al [8], Values of Ks may be obtained from the alternative options: field test using ASTM D1194-94; consolidation triaxial laboratory tests; CBR test; or empirical equation and tabulated values [2, 3].

Regarding conventional rigid method, q_a traditionally used in the design was assumed to be 120 KN/m3. Thereafter, it is required to convert (q_a) into equivalent Ks. Bowels [2] had reported an empirical relation between allowable bearing capacity of soil (q_{all}) and the modulus of subgrade reaction (Ks) of the footing based on a settlement (δ) of 25mm and ultimate bearing capacity (q_{ult}). Naeini et al [8] revealed that the equation 3 of Bowles was proposed by geotechnical consultants and therefore in this research the relation was applied to calculate Ks (14,400 KN/m3) supposing factor of safety (FS) equal to 3.

$$\mathrm{Ks} = 40\ \mathrm{FS}\ q_{all} \ldots\ldots\ldots\ldots\ldots (4)$$

$$q_{all} = \frac{q_{ult}}{\mathrm{FS}} \ldots\ldots\ldots\ldots\ldots\ldots\ldots (5)$$

3. RIGID METHOD DESIGN PROCEDURES

The conventional rigid method assumes two conditions [1]. Firstly, the mat is infinitely rigid, and therefore, the flexural deflection of the mat does not influence the soil pressure distribution. Secondly, the soil pressure is distributed in a straight line or a plane surface such that the centroid of the soil pressure coincides with the line of action of the resultant force of all the loads acting on the foundation. These two conditions may not introduce serious error for very stiff mats with fairly uniform column spacing and loads.

The mat foundation models were analyzed and designed using the conventional rigid method according to the procedure given by Das [3]. The plan of mat foundation models were divided into three design strips (3.5m, 5m, 3.5m) along x direction and four design strips (3.5m, 5m, 5m and 3.5m)in y direction as shown in Figure-1. Note that ACI 318-08 load factors (1.2 for dead loads and 1.6 for live loads) were applied to obtain factored loads.

4. SAFE PROGRAM DESIGN PROCEDURES

The equivalent mat foundation models used in rigid method were modelled, analysed, designed and detailed in SAFE v12.2 [10]. Firstly New Model Initialization window was used to choose the design code (ACI 318-08) and metric unit. Then with the help of Base Mat window, the mat was modelled through the input of dimensions of plan and modulus of subgrade reaction.

It is clear that SAFE program is based on finite element method where foundations are analyzed as plates or thick plates on elastic foundations. It uses modulus of subgrade reaction (Ks) that is specified for the foundation model and Ks is automatically converted into the compression of nodal springs.

The mat dimensions were entered in SAFE program and were automatically meshed based upon the maximum mesh dimension, in this model the SAFE program used a default element dimension 1.2 m by 1.2 m with the use of localized mesh and merging points. This meshing dimension was used as a fixed value. However, meshing has effect on the analysis. It is clear that design strips were edited as those used in conventional rigid method, see Figure 1.

The mat thickness is primarily input based on the thickness calculated in rigid method using punching shear provisions of (ACI-318-08, Section 11.11.2.1c) at the typical column locations. The mat thickness was edited and testified for checking it in SAFE program.

5. RESULTS AND DISCUSSION

The key parameter relating to supporting soil property is allowable bearing capacity (q_a) in rigid method and modulus of subgrade reaction (Ks) required in SAFE program. While q_a has been modeled to be 120 KN/m^2, the equivalent Ks is essential to make the comparison design meaningful. Using the equation 3, Ks is equal to 14400 KN/m^3.Furthermore, a parametric study have been conducted to understand the effect of Ks on the mat model analysis as flexural moment of Strip ABCD shown in Figure 2. .

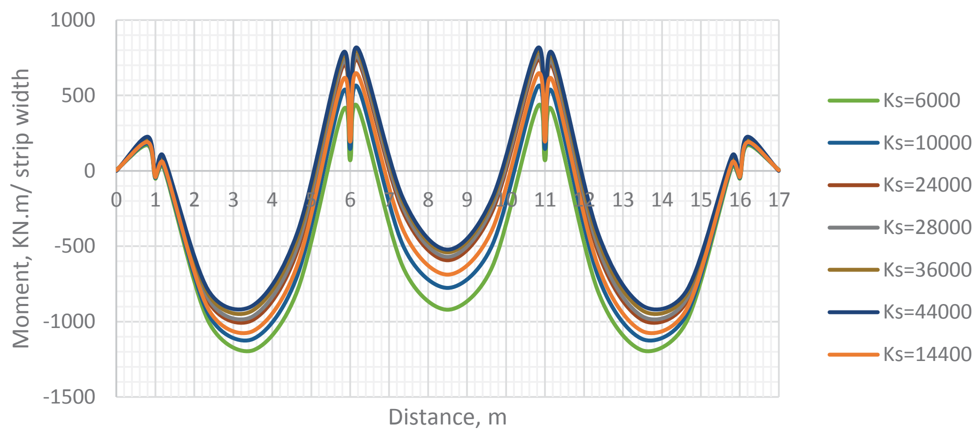


FIGURE 2. Parametric study for different Ks values of Strip ABCD

The Flexural moment have been drawn according to different Ks values from (6000 to 44000) KN/m^3. It was demonstrated that an increase in Ks values leads to a decrease of the positive moment in middle span between columns and an increase of negative moment around column loads. Therefore, the more accurate Ks investigated and evaluated before design, the more reliable design can be achieved in SAFE program.

As far as one way shear forces are concerned, one way shear diagrams per strip widths have been drawn for Strips ABCD, DCEF, ALIG and LKJI as shown in Figures 3 to 6, respectively. It can be noted that the amount of one way shear achieved by conventional rigid method is more than those given by SAFE program with the considerable fluctuations of their amounts among strips. For instance, in design strip ABCD maximum shear force is 1371 KN according to rigid method while SAFE program reports maximum enveloped shear force of 886 KN at the same location.

There are significant differences of one way shear obtained by both analysis procedures. Percent shear force differences of design Strips (ABCD, DCEF, ALIG and LKJI) are 35%, 39.8%, 11.6% and 53.6%, respectively. The differences in edge design strips are less than those of adjacent interior design strips. These differences could be various depending on column spacing, column loads and edge dimension of the mat plan. One way shear may not be critical in comparison of punching shear in more situation, but one way shear can be predominantly significant where the mats subjected to significant overturning loads from concrete core walls, shear walls, or braced frames [4]. Therefore, these one way shear force differences will need to be taken into consideration.

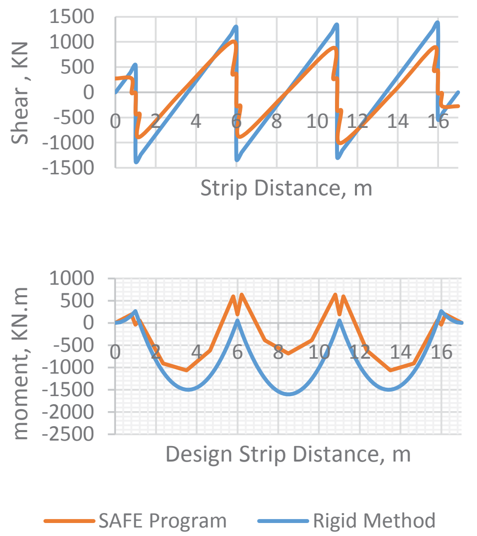


FIGURE 3. one way shear and moments using rigid and SAFE program for Strip ABCD

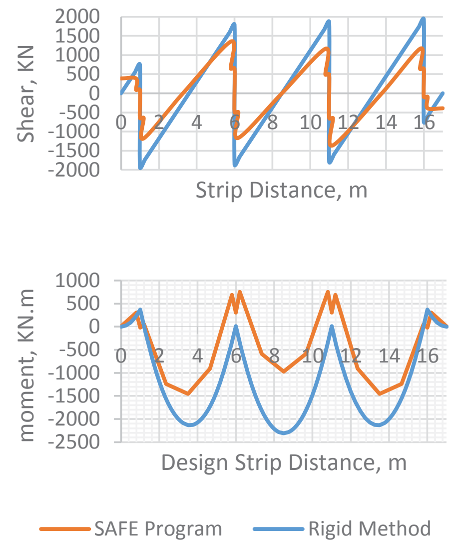


FIGURE 4. one way shear and moments using rigid and SAFE program for Strip DCEF

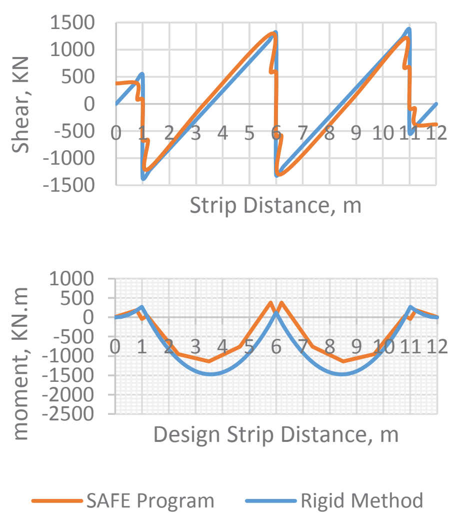


FIGURE 5. One way shear and moments using rigid and SAFE program for Strip ALIG

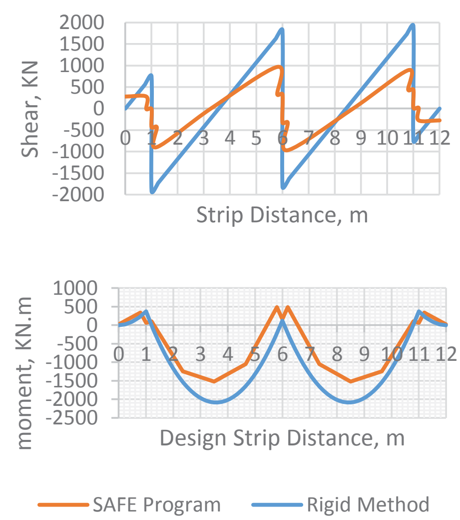
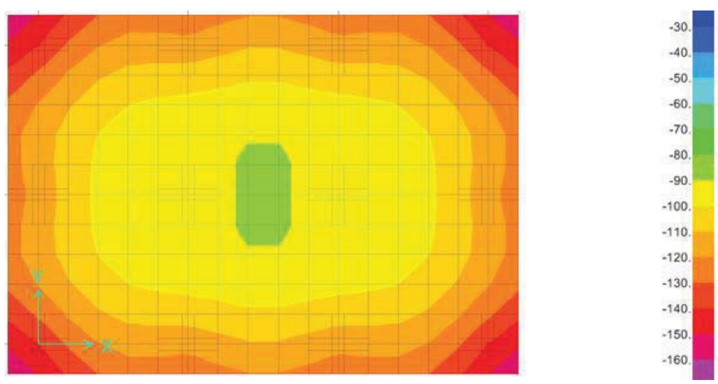


FIGURE 6. One way shear and moments using rigid and SAFE program for Strip LKJI.

With regard to flexural moments in the design strips as shown in Figures 3-6. Overall at middle spans, the rigid method analysis has given the highest amount of negative flexural moments whereas SAFE program has resulted in more positive flexural moments around column faces. Some fluctuations similar to v shape can be seen at column locations in the flexural moments using SAFE program. These fluctuation relates to the stiff area under columns to model column intersection as a stiff slab. Reference to design Strip ABCD, for instance, maximum negative flexural moment (1606 KN.m) have been obtained by rigid method at middle span (8.5m) while an enveloped negative flexural moment (688 KN.m) has been reported using SAFE program at the same distance. On the other hand, under column contact area maximum positive flexural moments of 56 KN.m and 636 KN.m have been gained by both rigid method and SAFE program, respectively.

With regard to contact soil reaction pressure under the mat model, soil pressure produced by service loads was 109 $\mathrm{KN/m^2}$ uniformed distributed according to the rigid method procedure and it checks allowable bearing capacity (120 $\mathrm{KN/m^2}$). However, the soil pressures in SAFE program were higher than allowable bearing capacity and especially in the edges and corners of the mat as shown in Figure 7.

These differences belongs to the flexibility of the mat which is reflected in SAFE program. Consequently, SAFE program can be considered as a tool in the evaluation of soil pressure capacity.



Note; Soil pressure are in KN/m2

FIGURE 7. Soil pressure under the mat in SAFE program

Punching shear often controls the critical thickness of the mat. In rigid method it can be calculated according to ACI 318-08 (Section 11.12.2.1) for the critical section at interior column and minimum required thickness is equal to 690mm. On the other hand, the foundation mat model needed more thickness to check punching shear ratio (Vu/Vc) in SAFE program as shown in Table 3.

TABLE 3.

Punching shear ratio vs thickness in SAFE program

Columns	Mat thickness in SAFE ,mm					
	600	625	650	675	690	700
Interior	1.2874	1.1965	1.1150	1.0416	1.001	0.9753
Edge	0.9492	0.8849	0.8270	0.7748	0.7459	0.7275
Corner	0.6737	0.6350	0.6252	0.6151	0.6088	0.6046

The punching shear ratio is calculated based on dividing maximum applied shear stress (Vu) by maximum concrete shear stress capacity (Vc), and less than one is accepted. Bringing punching ratio below one can be obtained by an adequate increase in mat thickness or compressive strength of concrete (fc').

In addition, an increase in modulus of subgrade reaction Ks could have a negligible effect on punching ratio. Ks were increased from (6,000 to 44,000) $\mathrm{KN/m^3}$ and it was revealed that punching ratio slightly increased but it is insignificant value. This is because of symmetrically distributed of column loads and applied punching loads depending significantly on applied shear stress (Vu) produced by the concentrated column loads.

6. CONCLUTION

This paper has presented the comparison of mat foundation design using rigid method and SAFE program through the use of the foundation modelling. Mat foundation models are analyzed as rigid body using the conventional rigid method and then SAFE v12 based on finite element method is applied to analyze and design the equivalent models, and the main focus was to investigate the results obtained from both methods.

In discussing analysis results, one way shear and flexural moments of design strip have been drawn for both methods and their differences have been shown that maximum positive and negative shear and moments of rigid method are greater than those of SAFE programs. Furthermore, SAFE program has given more flexural moments around columns, less flexural moments at strip mid span and thicker mat compared to corresponding results obtained in the rigid method. The author thinks that computer software application helps civil engineers to save time and solve complex cases efficiently, but civil engineers needs to use these programs carefully with understanding of modulus of soil subgrade reaction (Ks) and basic input parameters used in SAFE program.

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