Interdisciplinary Engineering for Resilience and Sustainability-based Prosperity of Nepal (ReSPro)

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***Abstract*— We generally view structural engineers as the designers of steel and concrete buildings and bridges, and architects their space organizers for comfort and functionality. We do understand that our designs ought to be safe, serviceable, economic and aesthetically pleasing. However, there are many other vital interdisciplinary mega projects that are key to our common national dream of Prosperous Nepal and Happy Nepali. These projects demand specialized input of civil and structural engineers and architects, among many other professionals, to ensure their disaster resilience as well as environmental and economic sustainability. Therefore, resilience and sustainability-based prosperity (ReSPro) is what Nepal should embrace as its infrastructure development philosophy. This presentation introduces three case studies of such ReSPro-based infrastructure research and innovation transformation initiatives, including multipurpose rockfill dams, rockfall protection structures, and rubber soil mix (RSM) base isolation system for vernacular and modern buildings.**

Keywords*— *Nepal, infrastructure development philosophy, interdisciplinary engineering, resilience, sustainability, prosperity, high dams, rockfall protection, reconstruction, rubber soil mix (RSM), smart structures

I. INTRODUCTION OF RESPRO

Nepal is one of developing countries with a current thrust on prosperity. The strong and stable Government of Nepal headed by RH Prime Minister KP Oli has formulated the slogan called "Prosperous Nepal and Happy Nepali". Accordingly, a large number of strategic and mega projects in the name of national pride projects have been announced, with some of them at the stage of DPR or construction. Energy and water (for irrigation, hydroelectricity, water supply, transportation etc.) roads and railways and smart cities are some of them.

When we think about prosperity and happiness through advanced infrastructure development, two aspects should come as integral considerations; viz. resilience and sustainability. The infrastructures should resist multi-hazard actions with particular focus on seismic forces and they ought to be environmentally sustainable with high green rating. Further, if we can make them "smart" with appropriate sensor network integration or use of smart materials, that would be even great. Therefore, resilience and sustainability based prosperity (ReSPro) transformation should be what we need to emphasize when we call Prosperous Nepal and Happy Nepali.

In this paper, based on the first author's decade-long advocacies and research leadership in the field of interdisciplinary structural engineering (ISE), three case studies of ReSPro philosophy as applied to the fields of high dams, roads and railways, and buildings are presented. They are explained in three separate sections and due reference is taken from previous and ongoing studies by the authors.

II. RESPRO THROUGH HIGH DAMS

A. Problem statement

Dams are the structures mainly meant to store water for its controlled use (regulated flow). Reservoir projects and the associated dams are spread all around the world. Embankment (Fill) dams cover the majority of them; more than 80%. International Commission of Large Dams (ICOLD) differentiates the rockfill dam from the earth-fill dam such that the former has its embankment consisting of rocks more than 50 % of its volume. Rockfill dam can further be classified as membrane (deck) type rockfill dam such as concrete faced rockfill dam (CFRD), and zoned type rockfill dam ('ZRD') such as the central clay core rockfill dam ('CCRD') with inverted filters in between the inner clay core and outer rockfill shells. Availability of local construction materials, high inherent stability and higher capacity to absorb shocks in extreme loading such as earthquakes mainly determine the selection of a zoned rockfill dam. Nepal, for example, (a small developing country but very rich in its hydro-potential) favors the construction of zoned rockfill dams. The existing dam of Kulekhani Hydroelectric Project (the only one seasonal storage project in Nepal) and that of many of the proposed storage projects such as Bagmati Multipurpose Project (an attractive project in the Eastern Region of the country) are of 'CCRD' type [1, 2]. Preferring any other type of dams against rockfill in the context of Nepal can be questionable.

Assuring the seepage and piping related problems are under control, the next important concern for the stability of a zoned rockfill dam in an earthquake event appears to be the stress deformation analysis. Again, despite the fact that stress analysis may have its own significance, deformations especially those leading to the loss of freeboard, should be given a prime importance [3-5]. In this connection, the prediction of potential displacement (settlement) of the embankment crest seems to be the most important response parameter in assessing the stability of a fill dam. Fig.1 is drawn to illustrate the phenomena [1].

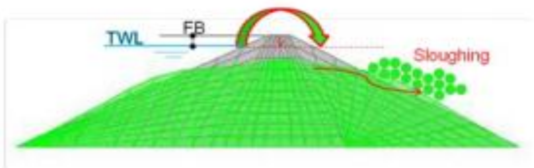
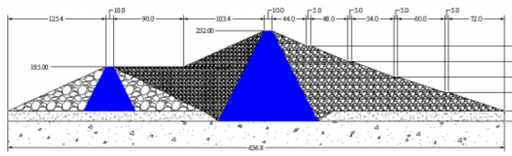


Fig. 1. Illustration of deformation as a seismic stability assessment parameter for an embankment dam

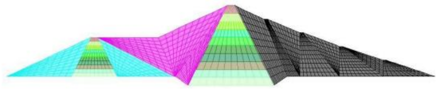
Conventionally, the fill dams are designed utilizing the empirical relations and slope stability is checked by limit equilibrium method (LEM) employing a number of trial failure surfaces to assure that the factor of safety (FoS) meets the requirement of minimum specified value. Therein, the earthquake effects are incorporated in terms of seismic coefficients. However, this method has several flaws; particularly it does not give any information about the deformations in the body of embankment to assess the dam stability against the loss of freeboard. A few researches are available which have used finite element analysis results to calculate the factors of safety by following the basics of LEM. But, again they are not free from the flaws of LEM. Further, the conclusion of the 13th international conference on large dams in 1979 was that “During earthquake resistant design of large dams or of important dams built in areas with high seismicity (PGA > 0.2 g), an appropriate dynamic analysis should be carried out with data as detailed as possible”. This is, in fact, true because the pseudo-static method when applied to a zoned rockfill dam, for example, concerns only a particular aspect of the behavior of the dam with respect to an earthquake. The problem of the seismic behavior of this type of dam is, however, more complex because of the very nature of the material. Therefore it seems essential to design a zoned rockfill dam by the dynamic method.

B. Results and conclusion

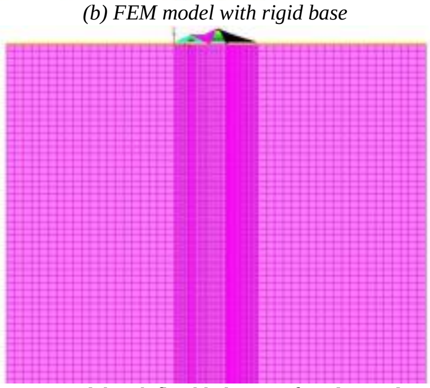
Some dynamic analysis results of stability assessment of the proposed rockfill dam of Bagmati High dam, using equivalent linear approach, implemented in general purpose FEM program of SAP2000, and based on Newmark's Analysis Procedure are presented in Fig. 2, whose details can be found in our previous work [1,2]. From the seismic stability analysis in terms of crest settlement of the rigid and flexible foundation finite element models, calculated from the respective acceleration response, which came out to be 1.20 m and 0.56 m, it is warranted that we become conservative in assigning freeboard during engineering design phase of rockfill dams. If rigorous seismic safety assessment is conducted for rockfill dams, there should be no argument that supports why we go for other type of dam. Therefore, rockfill dams are the great solutions for energy, irrigation, water supply, flood control and reservoir recreation favoring the spirit of ReSPro transformation of Nepal.



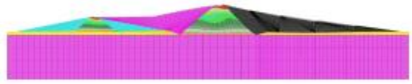
(a) Maximum cross section with clay core and rock shell



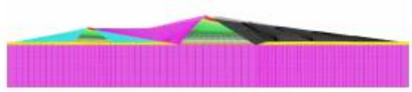
(b) FEM model with rigid base



(c) FEM model with flexible base or foundation domain

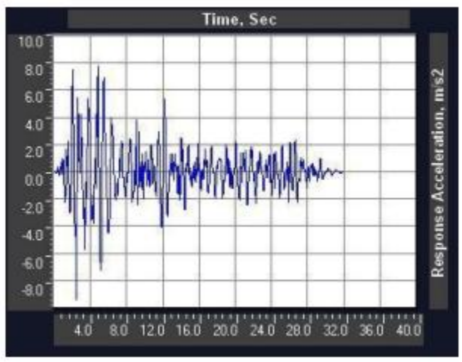


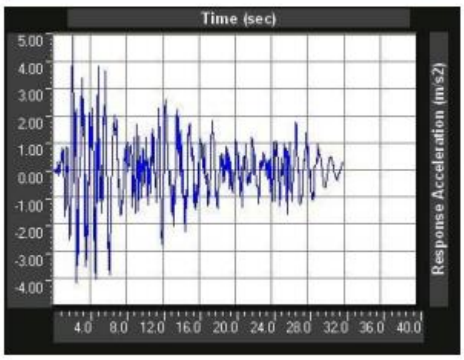
Mode 1



Mode 12

(d) Mode shapes with periods, respectively, 1 s and 0.5 s





(d) Crest acceleration time histories for rigid and flexible models

Fig. 2. Dynamic seismic analysis of Bagmati rockfill dam, Nepal

III. ReSPro through Rockfall Proection

A. Problem statement

Rockfall is an important geo-hazard of mountainous terrains around the globe and is gaining increased attention and recognition due primarily to the severe accidents and mortalities in mountain-highways and -railways, and even buildings in the hills. The 2015 Gorkha Nepal earthquake sequence, for instance, triggered a lot of fatal rockfall events along Kodari Highway of Nepal in Sindhupalchowk, and Siddhababa site in Siddhartha Highway is known to be one of the most hazardous areas for rockfall in Nepal [6, 7, 8].

Generally, we categorize the disciplines involved in slope stability engineering in Nepal as geology, engineering geology, geotechnical engineering and structural engineering and try to apply generalized knowledge and skills of these fields. However, rockfall engineering and rockfall protection engineering are such a specialized field of interdisciplinary engineering that demands an integrated knowledge and skills of all the aforementioned fields with emphasis on engineering mechanics and structural engineering, especially when it comes to analysis and design of intervention systems such as steel-dominant rock-nets and concrete-dominant rock-sheds. In this section, we show an example of a new type of steel cable-net structure called Long-span Pocket-type Rock-net (LPR) integrated with various friction-based energy dissipating brake devices [9,10] shown in Fig. 3.

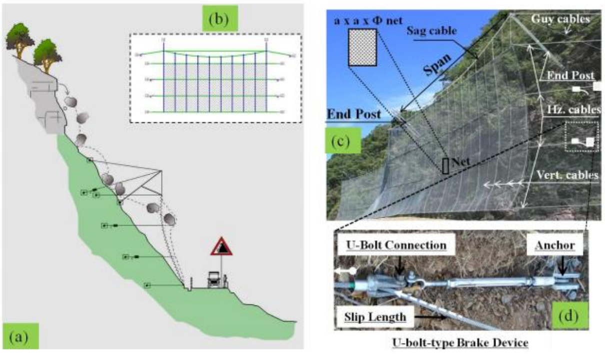


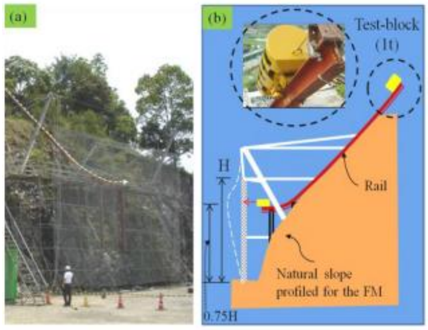
Fig. 3. A new type of rockfall protection cable-net structure, called Long-span Pocket-type Rock-net with U-bolt friction brake devices

B. Results and conclusion

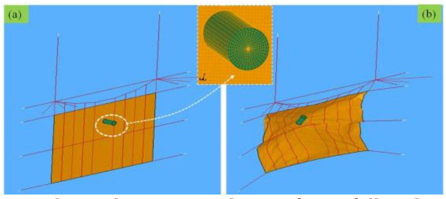
The LPR structure of 15 m span and 150 kJ energy was when modeled in the sophisticated FEM platform of LS-DYNA and analyzed for the non-linear dynamic behaviour of the structure with emphasis on out-of-plane deflection of the net at the point of rockfall contact as the significant response parameter with the tested constitutive models of each material used whose details can be found in [9], the full-scale test results could be accurately simulated. With such a calibrated and validated numerical model in place, a highly simplified analytical equation for predicting the displacement of the net was obtained as given below, by combining momentum and energy conservation equations:

$$\Delta = \sqrt{\frac{m}{\left(1+\frac{M}{m}\right)K}}V_0 + 2.135$$

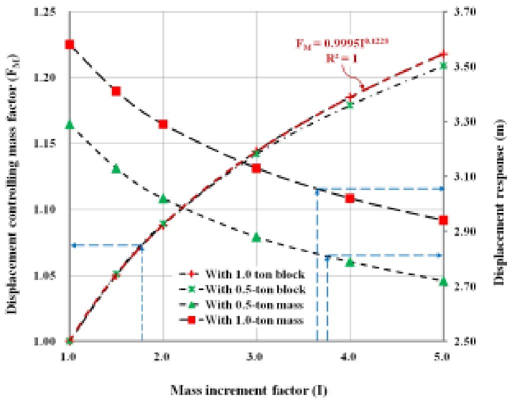
Furthermore, these numerical and analytical models were used to quantify and codify the effects of various parameters of the structural system as well as falling rock boulders and impact points. Some of these achievements are presented in Fig. 4.



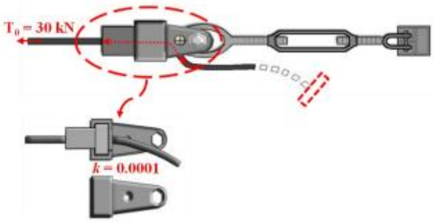
(a) Full-scale experimental tests of LPR



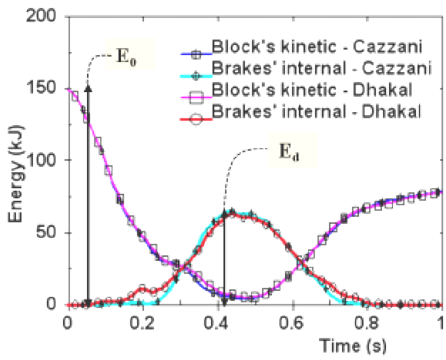
(b) Non-linear dynamic simulation of LPR full-scale test



(c) Displacement response of LPR as affected by mass increment of cable-net structure mostly via wire-mesh thickness and falling rock block mass



(c) Schematic drawing of Dhakal LPR brake model



(d) Energy dissipation evolution with Cazzani Brake Model and Dhakal-LPR Brake Model

Fig. 4. Experimental, numerical and analytical modelling and parametric study towards codification of parameters

Furthermore, most significantly, a new and efficient brake device for post-impact energy dissipation and stability of the structure called "Dhakal LPR Brake Model" was identified [10].

The positive implications and inspirations of such a study are that resilience and sustainability based prosperity (ReSPro), which comes from both less environmental interventions and disaster economy via our safer roads and railways planning and construction [e.g.], requires investment in rigorous research, which, in turn, help prepare our reliable national design codes and simplified but yet rational practice guidelines. Similar study is warranted for concrete-dominant rock-sheds that are highly suitable in the context of hill roads and railways that pass through steep slopes of rockfall hazards. In addition, new, low-cost and environmentally sustainable materials such as scrap tires to be used as cushion layer in the rock-sheds and ideally suitable in the context of should be promoted [12].

IV. ReSPro through Rubber Soil Mix (RSM)

A. Problem statement

Nepal is situated in seismically prone area with a population exceeding 30 million people. In its long standing history, Nepal has experienced multiple devastating earthquakes in the year 1255, 1408, 1505, 1833, 1934, and 2015 BS, each having magnitude greater or equal to 7.6 [13, 14]. The latest 25 April 2015 Gorkha Earthquake sequence alone caused serious casualties on humans with death toll exceeding 8500. In recent years, conventional method of earthquake resistant design by using Moment Resisting Frames (MRF) to improve seismic resilience of buildings has increased in the cities of Nepal. However, these MRFs are expected to show inelastic deformations and the repair cost for the extensive damage can be exorbitant [15]. Even for the developed country like New Zealand, as reported by Prof. Rajesh Dhakal in [16], the ramifications of earthquake brought a economic halt to the country. So, energy dissipating systems, especially for developing countries like Nepal, is necessary. However, the resource and technologies for hazard reduction using well-developed and sophisticated techniques of energy dissipation, doesn't seem economically viable in present context of Nepal. Thus, a possibly low-cost technologies, which also help save the environment, such as base isolation using Rubber and Soil Mixture [17] seems to benefit developing countries like Nepal.

Moreover, these days, we frequently talk about smart cities and smart infrastructures as an identity of prosperity in Nepal; however, smart cities when not seen from the point of view of resilience and sustainability can't deliver prosperity. The importance of resilience and economic post-disaster recovery [18] becomes more distinct when our cities feature high-rise buildings with irregularities dictated by architectural and functional requirements [19].

Not only for the purpose of dissipating horizontal and vertical seismic ground motions, but also one of the most elegant solutions that largely dissipates the shocks generated by events such as blasts and other excavation induced vibrations, while being economical, is again rubber soil mix (RSM) [20].

RSM is applicable to both vernacular (See Fig. 5 taken from [20]) and modern buildings [21] in rural and urban rebuilding or the smart cities proposed by the federal and state governments in various states and regions of Nepal. Indeed RSM is a boon for development countries like Nepal in support of ReSPro development policies.

In this section we present some of the fundamental research on RSM aligning with the spirit of ReSPro transformation through durable buildings.

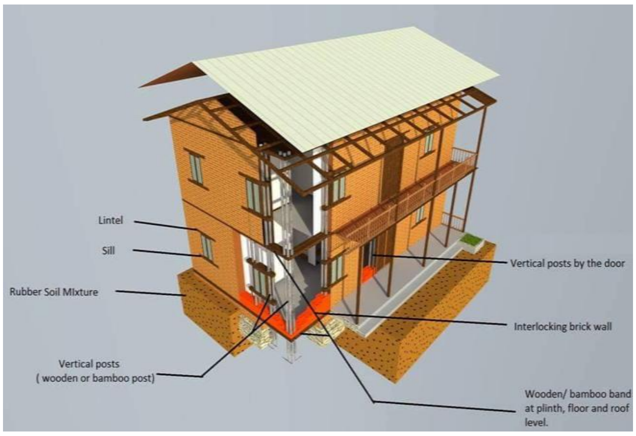


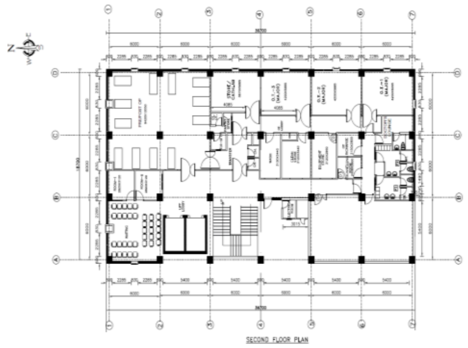
Fig. 5. Typical vernacular rural building made of interlocking brick walls and integrated with RSM

The numerical model developed in SAP 2000 with the architectural plans shown in Fig. 6(a), material models given in Table 1[22, 23] and Fig. 6 (b) is shown in Fig. 6 (c).

Table 1. Properties of normal soil and RSM

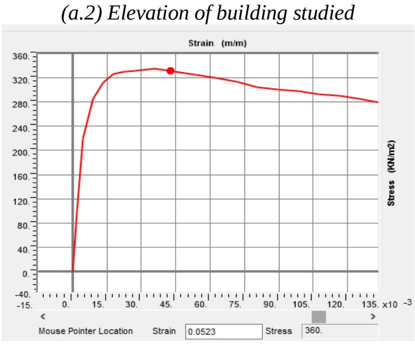
Properties	**Normal Soil**	**RSM 30%**
Density (Kg/m^3)	16.1	12.3
E (MPa)	250	90
G (MPa)	72.5	25.3
Frictional Angle (Degrees)	42.3	25.6

The results of non-linear time history analysis with normal soil and with optimum RSM of 30% (other results are not presented in this paper) and depth of 3 m, in the form of displacement and inter-story drifts, when subjected to El-Centro earthquake ground motion are plotted in Fig. 7. Clearly and very interestingly, the ppercentage reduction in maximum inter-story drift after the incorporation of is approximately 22.3%.

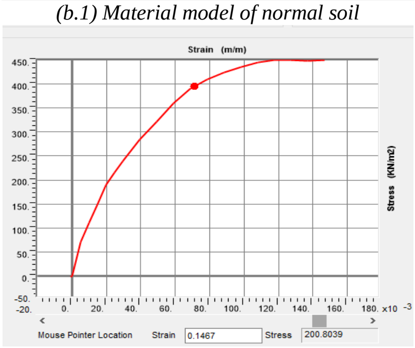


(a.1) Plan of building studied

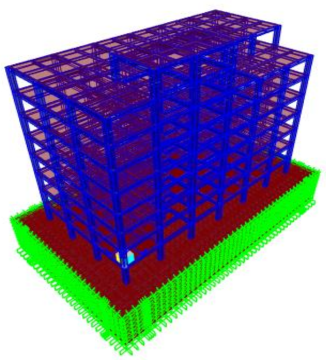
(a.2) Elevation of building studied



(b.1) Material model of normal soil

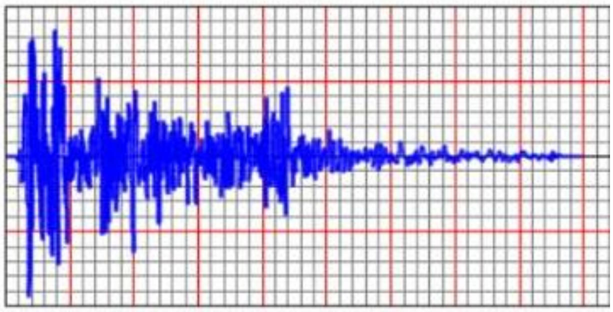


(b.2) Material model of RSM with 30% rubber content by weight



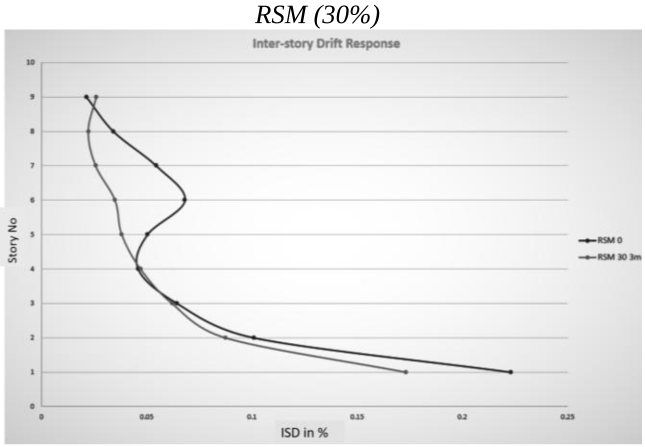
(c) Numerical model developed in SAP 2000

Fig. 6. Numerical modelling of modern building with RSM geotechnical base isolation system



(a) 1940 El-Centro earthquake

(b) Storey displacement response with normal soil and RSM (30%)



(c) Inter-story drift response with normal soil and RSM (30%)

Fig. 7. Seismic response comparison of building with and without RSM

V. CONCLUSIONS AND RECOMMENDATIONS

Nepal is one of high seismicity countries in the world, and also hit by other forms of shocks induced by various environmental hazards. Moreover, given its huge potentials of development of multi-purpose reservoirs, roads and railways along the hills and mountains, and smart cities in various regions of the country, also reflected on the manifestos of major political parties, and as committed by the Government of Nepal, with a slogan of Prosperous Nepal and Happy Nepali, the prosperity of Nepal is indeed inevitable. However, whether that prosperity is underpinned by the fundamentals philosophies of resilience against shocks and impacts, and environmental sustainability determines how durable the sought prosperity with a thrust on infrastructure development would become. Therefore, we recommend that the infrastructure development mission of Nepal should embrace resilience and sustainability based prosperity (ReSPro) transformation philosophy. Three case studies of interdisciplinary structural engineering (ISE) research and development in line with ReSPro philosophy, including high rockfill dams, rockfall protection structures and building structures with rubber soil mix base isolation system were presented in this paper, with separate explanation of each. It is believed that this paper not only enhances public awareness about these interdisciplinary mega projects, that form a part of what the Government of Nepal calls the national pride projects, demanding expert industry inputs of civil and structural engineers and architects, in particular, but also guides the passionate researchers of the possible new directions of research in these topical but less-researched areas. National codes and design guidelines of these infrastructure solutions despite huge scope in Nepal are lacking at the moment and the concerned stakeholders should invest more into these fields so that what we design and construct become rational and reliable too.

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