Contributions by Prof. M. N. VILADKAR in different areas of Geotechnical Engineering

Geotechnical Engineering encompasses fields of Soils & Foundations Engineering, Rock Mechanics & Rock Engineering, Soil - structure Interaction, and Underground structures. This nominee has research contributions in most of these areas:

1. **Static Soil-structure Interaction**
   i) Proposed methodology and finite element software codes for soil-structure interaction analysis of building frames, industrial chimneys, cooling towers etc. for 2D problems of plane frame structures resting on combined footings and also for 3D problems of space frame structures supported by isolated column foundations or resting on solid / annular raft foundations. These methods take in to account non-linear response of cohesion less materials and time dependent response of cohesive soils.
   ii) For finite element modelling of these problems, the nominee developed special two and three dimensional infinite elements appropriate to boundary simulation of semi-infinite soil media.

2. **Dynamic Soil-Structure Interaction**
   i) Proposed fracture mechanics based finite element methodology, algorithm and software code for transient dynamic analysis of building frame structures and underground bunkers against blast loading.
   ii) Also proposed Transient Transmitting Boundary (TTB), based on extrapolation techniques, for boundary simulation of problems mentioned in 2 (i) above.
   iii) Proposed fracture mechanics based finite element methodology, algorithm and software code for transient dynamic analysis of dam-foundation interaction problems in time domain, including the simulation of reservoir effect and the TTB for earthquake loading.

3. **Rock Mechanics & Rock Engineering**

This field includes analysis and design of large underground tunnels, shafts, and caverns (Chambers) and various underground structures. This field has applications in areas like hydro-power projects, nuclear waste repositories, large underground storages for petroleum products, technical facilities for defense services for storage of ammunition, explosives, missiles etc. The Himalayan geology is known to be very complex and fragile. The rock mass is highly jointed, fractured and weathered. There exist large geological discontinuities like folds, faults, shear zones, thrust zones, etc. These discontinuities have tremendous influence in the deformation and stress-strain response. Moreover, there is a large tectonic activity in the region. The whole northern region lies either in zone-IV or zone-V of the earthquake zoning map of India. Design of support systems for large underground excavations in such geological formations is a very challenging problem. The deformational and stress-strain response of tunnels and caverns is governed by the rock mass quality, the depth of overburden, nature and magnitude of in-situ stresses, and the hydro-geological conditions.
The nominee has proposed /developed:

i) Various empirical approaches for prediction of various ground conditions for tunneling depending upon the rock mass parameters at any site. This prediction is extremely essential before bids are invited for undertaking tunneling projects so that construction agency is aware of the type of ground through which it has to do tunneling, probable nature of the support system that will have to be provided, and it can as well keep contingency provisions ready to meet any undesirable conditions during tunneling.

ii) Methods for rock mass-tunnel support interaction analysis, especially for predicting ground response curve and the support reaction curve, and hence predict conditions of stability of tunnel.

iii) In Himalayan region, typical hydro-geological conditions can give rise to serious problems during construction resulting in delays in the completion of projects. This nominee has proposed methods for prediction of pre and post construction saturation pressures and how to account for such pressures in design.

iv) The nominee has also proposed constitutive laws (stress-strain relationships) for jointed rock masses which take into account no. of joint sets in rock mass and also the dip and dip direction of each joint set. These laws also account for the nature of joint surfaces.

v) Major geological discontinuities like faults and shear zones, which travel over considerable distances, have their own dip and orientation and may as well have presence of gouge materials. Intersection of such a discontinuity or its presence in the vicinity of an underground excavation, which if goes undetected during initial investigations, can cause the failure of the excavation. In order to investigate its influence on stability of excavation, it is essential to represent such a major discontinuity in numerical modelling of the problem. The nominee has developed the most generalized stiffness formulation of a three dimensional interface element which can take into account any shear deformation along the planar / arbitrarily curved surface of the discontinuity.

vi) The nominee has also proposed solution methodology for coupled stress-flow analysis of large underground caverns generally constructed for underground power house structures, de-silting chambers, surge tanks, and large storage facilities. The method facilitates design of support systems of excavations wherein the rock mass surrounding it is already saturated or is likely to get saturated in the post construction period.

4. Analysis & Design of Underground Structures (Metro Underground Tunnels)

Underground Structures are strategic elements in transportation and utility networks like for example tunnels in metropolitan cities for mass rapid transit system (MRTS). Historically, these structures were considered less vulnerable to earthquakes. However, they cannot be treated as completely exempt to effects of ground shaking as demonstrated by the significant damage suffered during the 1995 Kobe (Japan) earthquake, 1999 Chi-Chi (Taiwan) earthquake, and 2004 Niigata (Japan) earthquake. The growing need to enlarge these transportation networks across the length and breadth of the country is the cause of renewed interest for studying the vulnerability of such facilities to seismic loading. A large earthquake would not only cause potential loss of human lives but can also damage other infrastructure which can result in severe economic losses, especially in view of the time required to restore the functionality of the
network. In order to reduce the potential loss of serviceability, it is essential to reduce the possible risk associated with such structures and the effects of damage. From this point of view, the nominee investigated the problem of seismic response of Delhi metro underground tunnels (zone-IV of earthquake) to 1991 Uttarkashi and 1999 Chamoli earthquakes. Investigations were carried out both in 2D and 3D which led to following significant conclusions:

i) Displacements in soil-tunnel system and the forces in RC liners were found to increase significantly due to application of both horizontal and the vertical components of earthquakes. Values of shear force and bending moment developed in RC liners and obtained via 2D plane – strain elastic analysis were quite comparable with those obtained via available elastic solutions in literature. It was realized that both horizontal and vertical components of earthquake should be considered for the response analysis and the final designs be carried out for that component of earthquake which would produce higher damage in tunnels.

ii) Dynamic response of underground metro tunnels was found to be subdued due to plastic behavior of soil, especially due to dissipation of strain energy during the earthquake through plastic regions in soil-tunnel system. Elastic analysis therefore, is not adequate for the seismic design of tunnels because it may overestimate the dynamic response which would lead to an uneconomical design. Overburden depth of tunnel and the peak ground acceleration (PGA) are the most important parameters from the point of view of seismic design, dynamic response of shallow tunnels was found to increase significantly with increase in PGA and reduce with increase in depth of overburden above the tunnel.

iii) In a three dimensional dynamic analysis, it became obvious that horizontal (X-direction), vertical (Z-direction) and longitudinal (Y-direction) displacements in soil-tunnel system attain their maxima values at the ground surface during the earthquake. Higher values of displacements were experienced when soil-tunnel system was subjected to T, V, L components of earthquake, respectively. But residual forces in RC liners were found to increase significantly when the L (Y-direction) component of earthquake was applied along the axis of tunnel. Absorbent boundary was found to be more effective for the dynamic analysis as compared to elementary and free-field boundaries.

iv) Dynamic response of soil-tunnel system was found to be greater due to combined dynamic loading of moving train and horizontal (T) component of earthquake as compared to response due to sole loading of train in motion or due to earthquake alone. This response reduces with increase in overburden depth of tunnel for all cases of dynamic loadings. Therefore for minimizing the effect of dynamic loadings at ground surface, selection of overburden depth is very critical. Overburden depth of tunnel should be so chosen that ground surface is not affected.

v) The chosen alignment of Delhi metro tunnels was found to be safe against the liquefaction phenomenon for T (X-direction) and V (Z-direction) components of Chamoli earthquake but liquefaction has been found to occur when L component (Y-direction) of Chamoli earthquake was applied parallel or nearly parallel to the alignment of tunnel. In the prevailing condition (i.e. Water table depth, h = 17m), soil-tunnel system is safe against liquefaction for T component of Chamoli earthquake. However, it can liquefy in case the water table rises above the tunnel crown. The site was found to be safe against liquefaction for Chamoli earthquake even when the PGA of T (X-direction) component of earthquake was scaled up to 4.0 m/sec². Beyond this PGA, chances of soil liquefaction would enhance.
vi) **From the stand point of geotechnical practice**, it can be inferred that – 

a) For such metro tunneling projects, it is essential to consider site specific earthquake response spectra for their analysis and design so as to get realistic response of the soil-tunnel system, 

b) Three dimensional analysis of soil-tunnel system to all the three components of earthquake gives a realistic picture about the deformation behavior of tunnels, especially actual displacements are much smaller than those obtained from a two dimensional analysis, 

c) Even though the loading due to motion of metro train and the earthquake are not in the same phase, response of soil-tunnel system to such a superposed loading gives an idea regarding if such a response is detrimental to the passengers travelling in the train, and 

d) It is extremely essential to understand the response of the system to liquefaction, especially if there is a likelihood of ground water table rising above the crown of the tunnel.

5. **Foundation Engineering**

Foundations of many engineering structures in hilly areas are sometimes placed near the edge of a slope. Abutments of bridges, transmission line towers, and buildings and retaining structures constructed adjacent to ravines are some examples of foundations placed on upper surface of a slope. The foundations of such structures are subjected to eccentric-inclined loads due to moments and horizontal thrusts in addition to the vertical loads. The main criteria for a satisfactory design of foundations of such structures are the ultimate bearing capacity, permissible settlement, tilt and the overall stability of the slope. With this in view, theoretical and experimental investigations were conducted to understand the behavior of strip footings placed near the edge of a slope and subjected to an eccentric-inclined load. The analytical work included development of methodologies to predict the ultimate bearing capacity and the pressure-settlement and pressure-tilt characteristics of such footing. The experimental work was aimed at obtaining the ultimate bearing capacity, the pressure-settlement and the pressure-tilt characteristics of a model strip footing placed on a sand slope and subjected to eccentric-inclined loads. The study led to following conclusions: 

i) **Footings on level surface but under eccentric inclined loads:** Based on – a) nonlinear elastic and elasto-plastic analysis of footings on cohesion less soils, b) the experimental study, and c) parametric study, non-dimensional correlations were proposed to predict the vertical settlement, horizontal displacement and the tilt of the footings. The influencing parameters are: friction angle, $\phi$ of soil; load inclination angle, $i$°; footing width, $B$; and eccentricity ratio, $e/B$. These can be used directly for the design of foundations under eccentric inclined loads. 

ii) **Ultimate Bearing Capacity for footings on slope:** A theory based on limit equilibrium approach was proposed for determining the bearing capacity of a strip footing on the upper surface of a slope and subjected to eccentric-inclined load using the concept of one sided failure. The results were presented in terms of non-dimensional bearing capacity factors $N_p$, $N_q$, $N_c$, which depend upon non-dimensional parameters soil friction angle, $\phi$; slope angle, $\beta$; $D_f/B$; foundation depth to foundation width ratio, $D_f/B$; eccentricity to footing width ratio, $e/B$; and load inclination angle, $i$. These bearing capacity factors have been presented in the form of charts convenient for use in design.
iii) Pressure-Settlement and Pressure-Tilt Characteristics for footings on slope: A procedure was proposed to predict the pressure-settlement and pressure-tilt characteristics of a strip footing resting on top of a slope and subjected to an eccentric-inclined load, using non-linear constitutive laws of soil.