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Basic parameters of small underground nuclear power stations

Osnovni parametri majhnih podzemnih nukleark

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Abstract

The use of underground space for various needs has seen a significant growth in recent year. This possibility is also reflected in the concept of construction underground nuclear facilities. Based on previous experience, success in the future might be bound to such as smaller nuclear facilities by some named as Small Modular Reactors (SMRs). Suitable locations at appropriate depth taking advantage of the natural barrier properties afforded by the good quality bedrock have important influence on providing appropriate natural circumstances for SMRs. Underground sitting can provide superior protection compared to that of a surface serviced sitting in many critical situations and subsequent devastating consequences for the operation of a nuclear facility. Complicated underground complex needed for a nuclear power system need special attention calling for dedicated investigations and also research on such as issues as earthquake hazard, although the latter seems to be documented being advantageous already. The paper will present a case that clearly shows the obvious advantages of the use of underground space for current available nuclear technologies and assessments of seismic loads influences on nuclear underground structures.

Key words: underground space, underground nuclear station, natural containment, seismic loading, rock mass displacement

Izvleček

Izraba podzemnega prostora v zadnjem času hitro narašča. Prav tako je zaznati povečane aktivnosti pri izdelavi konceptov gradnje podzemnih nuklearnih objektov vključno z majhnimi nuklearkami, ki bi bile opremljene s tako imenovanimi majhnimi modularnimi reaktorji (Small Modular Reactors – SMRs). Primerne lokacije za gradnjo tovrstnih objektov v optimalnih globinah in trdnem hribinskem okolju imajo veliko prednosti pred nuklearnimi objekti na površini, saj zagotavljajo naravni sistem zadrževalnikov in neprimerno višjo varnost tovrstnih občutljivih objektov ter realno možnost namestitve majhnih modularnih reaktorjev (SMRs). Navedene prednosti so v času gradnje, obratovanja in zaprtja predvsem v smislu varnega izvajanja del v različnih naravnih okoljih, ki so izpostavljena različnim spremljajočim tveganjem ob pozitivnem vplivu na trajnostni razvoj širših območij. Glede na zadnje zahteve pristojnih institucij, ki spremljajo varnost obratovanja nuklearnih objektov, je treba posebno pozornost posvetiti raziskavam tveganj, ki so povezana s seizmičnimi vplivi na kompleksen sistem podzemnih nuklearnih objektov. V tem prispevku so podane možnosti in prednosti, ki jih daje podzemni prostor sedanjim tehnologijam na področju gradnje majhnih podzemnih nukleark, ter ocene stabilnosti objektov glede izpostavljenosti različnim seizmičnim obremenitvam.

Ključne besede: podzemni prostor, podzemna nuklearka, naravni zadrževalnik, seizmična obtežba, pomiki hribine

Introduction

The use of underground space for various needs in recent years is also reflected in an increased need of looking at construction of small nuclear power stations underground. The reason is partly related to the events which struck us all causing the tragically accident in certain areas and populations as terrorism showed a new face and partly the devastating consequences of natural catastrophes. To mention only two such incidents, one is of course the attacks in USA on September 11, 2001 when terrorists attacked hit the World Trade Center and other symbolic buildings and the other one is the earthquake that surfaced in the area of Fukushima (March 11, 2011) severely damaging a nuclear power last year. In addition to these incidents terrorist threats take place every day around the world and catastrophic weather events cause incomparable damage and heavy human casualties. In that constellation in the future we can expect an increased need for energy, complying and coinciding with an increase number of people living on the Blue Planet. What will be the correlation relationship is difficult to predict today, hopefully it will not be linear. In the 70's it was experienced that safe and secure solutions to build underground nuclear power plants were too expensive to pay off the investment at that time. Today cost estimates per unite single and four installations, using drill and blast produce around 90 $ million to 45 $ per reactor, but for TBM solution the cost is around 25 $ to 15 $ million per reactor[1]. The construction of multiple reactors in single locations is possible in high quality rock environment, self-supporting, with low seismic motion. That technical solution reduces capital cost with using new technologies and techniques for underground construction and reduces life cycle costs and new concept for waste management. A rough estimate of the cost of construction and operation shown expected goal that underground nuclear park concept with 1 000 MW has about 60 years lifetime, with 10 % saving (Figure 1).

Experiences with the underground space use for nuclear activities

In the past there have been several projects that address technical solutions to the implementation of underground nuclear power plants. As already mentioned, in the 70's the technological and cost barriers were show stoppers for carrying out such projects on a large scale. Practically all the nuclear power plants were built on ground surface with deep cuts and excavations to cope with the technological requirements that were applicable to the construction of nuclear power facilities at that time. In the last three decades there were

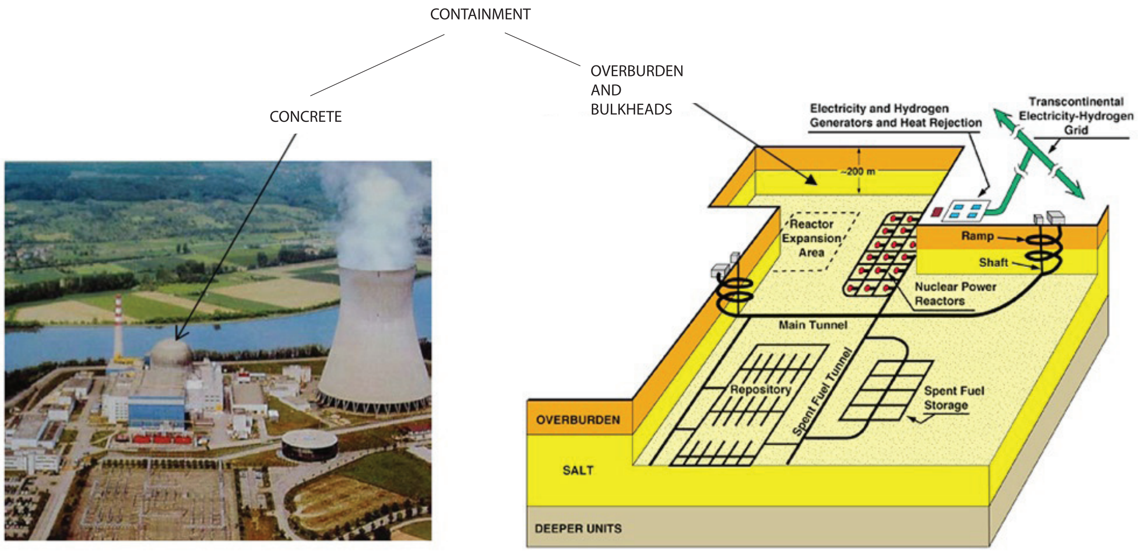


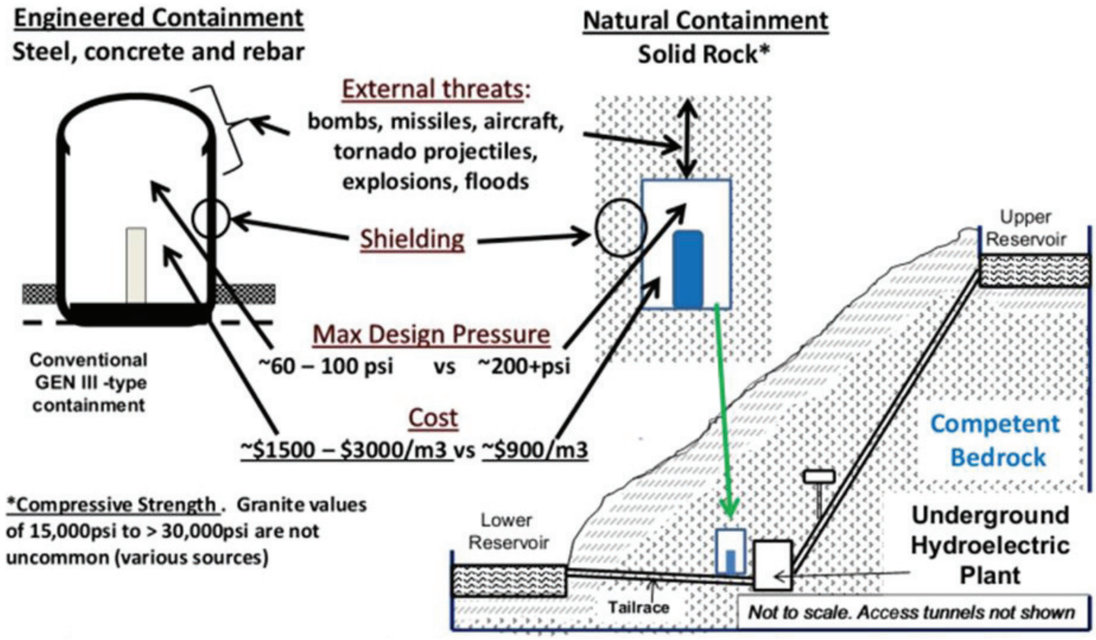
Figure 1: *Elimination of need conventional containment structure*[1].

several feasibility studies of underground nuclear power stations undertaken in Canada, USA, Japan, Switzerland and elsewhere. Most of the studies showed positive results in favor of construction of such facilities. It was found that the underground nuclear power plants have many advantages over those that are built on the surface. Specifically highlighted were the aspects of safety and protection against external influences and catastrophic events such as earthquakes, military activities and terrorism and sabotage. The studies prepared in the 70's concluded that there would be an almost certain schedule and cost increase caused by the construction of the underground nuclear facilities and possible cost increase during the operation of the power plants. Underground hydroelectric power plants provides potentially opportunities to exploit the advantages and experiences offered by underground citing in hard rock environment as regards the safety of underground construction and operation of nuclear power plants. Therefore, in the following we will dedicate the paper to aspects of utilizing the capabilities of the rock mass to host underground sittings of nuclear power facilities and the many advantages that accompanies the kind of usage.

Worldwide there are already a number of existing underground structures of various kinds and valuable experience has been gained from the construction and operation of underground hydroelectric power plants. Not so far ago it was shown that it is often a limiting factor in the construction of underground facilities for different purposes due to geological risk because of adverse rock conditions that could potentially cause significantly higher cost of construction. This has a strong influence on final costs of such underground facilities. In the goal to avoid such difficulties in proper time, there is still a need of high quality knowledge of mechanical, thermal, hydrological and geochemical properties of ground.

In the field of underground space applied widely for the development of underground hydro power plant, the experience from Norway is likely one of the best in the world. In explanation the hydropower plant Sima is situated 700 m inside a valley side at Simadalen. It has a static head of water of 1 158 m and is the second largest power station in Norway.

Figure 2 shows the schematic possibility of establishing nuclear facilities combined with hydroelectric power plants.



Conclusion: SMR containment chambers in suitable bedrock at adequate depth could provide increased margins of safety for DBA/Ts, reduced consequences for Beyond-DBA/Ts, and reduced financial risk for future changes to the DBT---all at lower cost.

Figure 2: *Potential location of SMRs containment chamber*[1, 2].

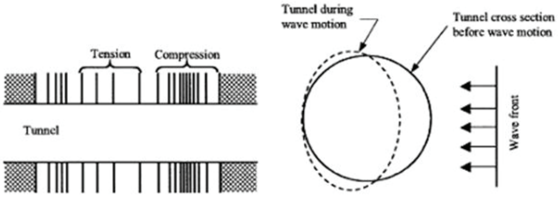
Earthquake sensitivity

Underground facilities are an integral part of the infrastructure of modern societies and are used for a wide range of applications, including subways and railways, highways, material storage, and sewage and water transport. A future need exists to look closer at the possibility of developing underground solutions for nuclear facilities also. When the surface area is subject to and also sensitive to earthquake activity and loading, underground utilization should be analyzed on seismic and static loading. Although in the past it has been documented that the underground structures are significantly less prone to seismic risk than those on the surface. The results of professional research works and their conclusions are accessible and confirm the above statement. The currently available risk assessment methods allow analyzing the magnitude of risk for different input parameters of seismic loads in different ground environment. A few authors, like Dowding & Rozen[3], also proposed a correlation between tunnel damage and peak ground acceleration (PGA) calculated at the free surface immediately above the tunnel through an attenuation law. They suggest that "minor damage" is expected when the value of PGA ranges between 0.19 g and 0.50 g. The corresponding thresholds for peak particle velocity (PGV) range approximately between 20 cm/s and 90 cm/s.

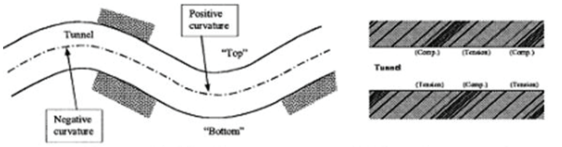
Design analyses of underground structures

Assessing the seismic response of an underground structure is a challenge which is significantly different from that of a corresponding above-ground facility since the overall mass of the structure is usually small compared with the mass of the surrounding soil and the overall confinement acts as a strong damper of the seismic excitation. The development of appropriate ground motion parameters, including peak accelerations and velocities, target response spectra, and ground motion time histories, is briefly described by Hashash[4].

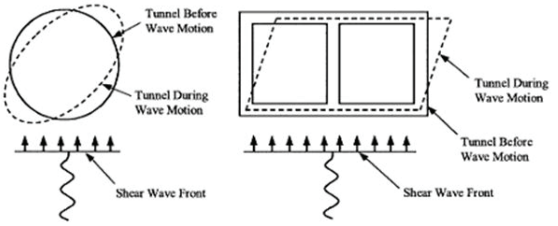
Based on previous statements the "minor damage" is expected when the value of PGA ranges between 0.19 g and 0.5 g and corresponding thresholds for PGV range approximately between 20 cm/s and 90 cm/s, also Power[5] proposed a damage classification based on PGA. For ground shaking less than about 0.2 g very little damage occurred in tunnels; in the range of about 0.2 g to 0.5 g, some cases of damage were reported, ranging from slight to heavy (serious damage only occurred in an unlined tunnel and in a tunnel with timber or masonry linings); for PGA exceeding 0.5 g there were a number of instances of slight to heavy damage (serious damage occurred only in a tunnel with unreinforced concrete lining).



(a) Compression-extension (b) Compression of tunnel section



(c) Longitudinal bending (d) Diagonally-propagating wave



(e) Ovaling of tunnel section (f) Racking of tunnel section

Figure 3: *Modes of the tunnels deformation due to seismic waves, (After Owen and Scholl, 1981 cited in Hashash[4]).*

Analysis of seismic loading on underground caverns sited in rock mass

The Phase2 – finite element modeling computer program Rocscience[6] has a module which allows analysis of seismic loading on underground structures. It is based on pseudo-static approach, where the additional seismic force is calculated as a product of the specified seismic coefficient, a dimensionless vector and the amplitude of the body force, which is the self-weight of a finite element. In absence of more accurate site-specific depth reduction factor models, the guideline in Hashash et al.[4] as shown in Table 1 can be used.

Table 1: *Ratios of ground motion at depth to motion at ground surface. (After Power et al.1996, cited in Hashash[4])*

Tunnel depth [m]	Ratio of ground motion at tunnel depth to ratio of surface ground motion
≤ 6	1.0
6–15	0.9
15–30	0.8
≥ 30	0.7

For instance, a seismic coefficient of 0.30 used in a model in Phase2, which is the seismic coefficient at tunnel depth of 100 m, corresponds to a seismic coefficient of 0.30/0.70 ≈ 0.43 at ground surface.

A number of numerical analysis on case studies was carried out to investigate the effect of vertical seismic coefficient which is using the pseudo-static seismic loading procedure in Phase2. In the present model a total of five seismic loading scenarios including one case without seismic loading were analyzed. The model which has been applied in the numerical simulation consists of two rock caverns at a depth of 100 m below surface, one big and the other smaller. The dimensions for the large cavern are: $W_B = 22$ m, $H_B = 46$ m and smaller one has the following dimensions: $W_s = 13$ m and $H_s = 17$ m. The length of each cavern is 170 m. The rock mass quality is proposed by Mohr-Coulomb constitutive model with geotechnical and mechanical parameters which is presented in Table 2. The different cases of seismic loading were included in the model in the third and latest stage when both caverns were stabilized with 10 m long cable bolts with capacity 0.6 MN and 10 cm thick FRS (Fibre Reinforced Shotcrete), as shown in Figure 4a. Results of parametrical investigations used Phase2 code had clear goal to explain what amount of stress-strain changes can be expected related to seismic loading in different directions (Figure 5).

The general assessment was considered being very optimistic because obtained results which are shown on the next figures arrive at the conclusions which were proved in the previous investigations. The model was developed for two underground caverns sited in quite stable rock mass and with a virtually horizontal fault zone of 12 m in thickness. This is located in the central part of the third height of the bigger cavern. This virtual and rather simplified geological base case also has demonstrated the influence of weakness zone on the stability of both the bigger and smaller cavern.

The dimensions of these caverns are in practice quite similar to what can be expected in the future as far as size wise is concerned for underground structures of underground hydro

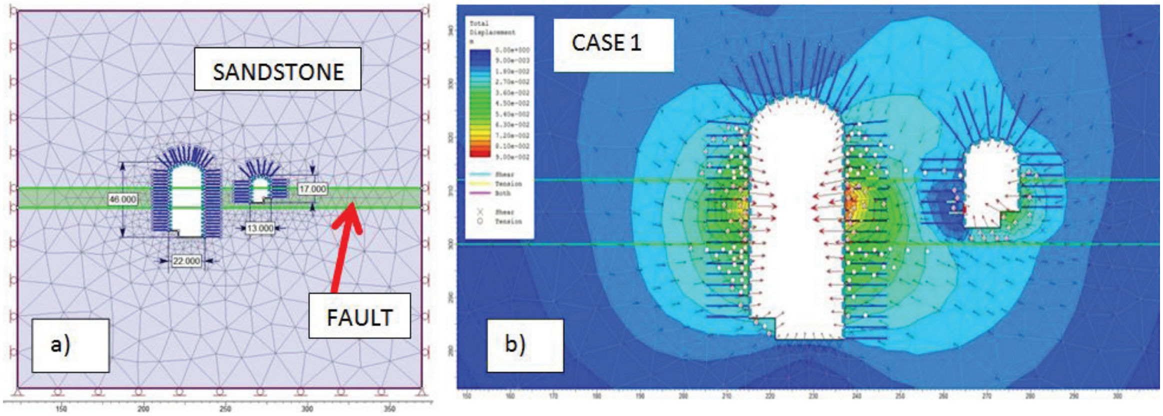


Figure 4: *a) Vertical cross section through caverns with dimensions and support elements, b) CASE 1 - maximal calculated displacement without seismic loading.*

power plants and future SMRs incorporated in small underground nuclear power plants.

In Figure 5 the changes of maximum displacements are presented for four cases in which different combinations of horizontal and vertical seismic coefficients are included in the FEM numerical analysis. The significant differences in the calculated results have been caused by the adequate responses of rock mass – support system. One of the main consequences of increasing the main stress values is the vertical seismic coefficients Kv, which is directed downward in the same direction as Earth's gravity (CASE 4 and CASE 5). In Figure 4 where the contour plots of the total displacements for the four loading cases are described it can be concluded that the distribution of the total calculated displacement around the caverns periphery generally resembles an ellipse.

The maximum stresses appear along the horizontal axis of the ellipse. At the same time the direction of the horizontal component of the primary stress is bigger than the vertical component and influencing on the stress compensating. This means, if an anisotropic primary stress field exists, the influence of seismic loading in horizontal direction does not have a decisive influence on general stability on the analyzed caverns. Altering the direction of the vertical seismic coefficient does not result in any drastic change in the location of the long-axis of the ellipse. The magnitude of the stresses around the tunnel is greater when the direction of the vertical seismic coefficient is downward (negative), in the same direction as the gravitational force.

Since the CASE 2 is where $K_h = 0.30$ and the vertical seismic coefficient was ignored, the CASE 2 and CASE 3 are compared with CASE 1, but last two cases (4, 5) have distinguished differences compared to first three load cases, which come from the effect of the vertical seismic coefficient.

From the diagrams in Figure 6 it can be concluded that the effect of vertical seismic coefficient is significant in Cases 4 and 5. The similar can be found in these two cases, when a comparison is done on stress fields where main stresses increased.

Table 2: *Some important input parameters for FEM analysis*

Field stress: gravity	
Using actual ground surface	
Total stress ratio (horizontal/vertical in-plane): 1.5	
Total stress ratio (horizontal/vertical out-of-plane): 1.5	
1. Material: sandstone	
Unit weight	0.027 MN/m^3
Young's modulus	4 500 MPa
Poisson's ratio	0.25
Peak tensile strength	0 MPa
Residual tensile strength	0 MPa
Peak friction angle	45 degrees
Peak cohesion	0.8 MPa
Residual Friction Angle	25 degrees
Residual Cohesion	0.1 MPa
Unit weight of overburden	0.027 MN/m^3
2. Material: fault	
Unit weight	0.027 MN/m^3
Young's modulus	3 000 MPa
Poisson's ratio	0.3
Peak friction angle	35 degrees
Peak cohesion	0.2 MPa
Residual Friction Angle	25 degrees
Residual Cohesion	0.1 MPa
Liner: shotcrete	
Liner Type	Standard
Beam Formulation	Timoshenko
Thickness	0.1 m
Young's modulus	15 000 MPa
Poisson's ratio	0.25
Strength Parameters	
Peak compressive strength	40 MPa
Residual compressive strength	20 MPa
Peak tensile strength	8 MPa
Residual tensile strength	1 MPa
Bolt Properties	
Bolt Type	Fully bonded bolt
Diameter	30 mm
Young's modulus	200 000 MPa
Tensile capacity	0.6 MN
Residual Tensile capacity	0.6 MN
Pre-tensioning	0 MN
Out-of-plane spacing	2 m
Allow Joints to Shear Bolt	Yes

In the analyzed point B in the large cavern it was further identified small damages on the primary shotcrete lining of the smaller cavern. The calculated total displacement in the analyzed points showed similar conclusions, except that the reductions of displacements due to point A where the compensation between secondary stresses and stresses in the system caused by seismic loads are present.

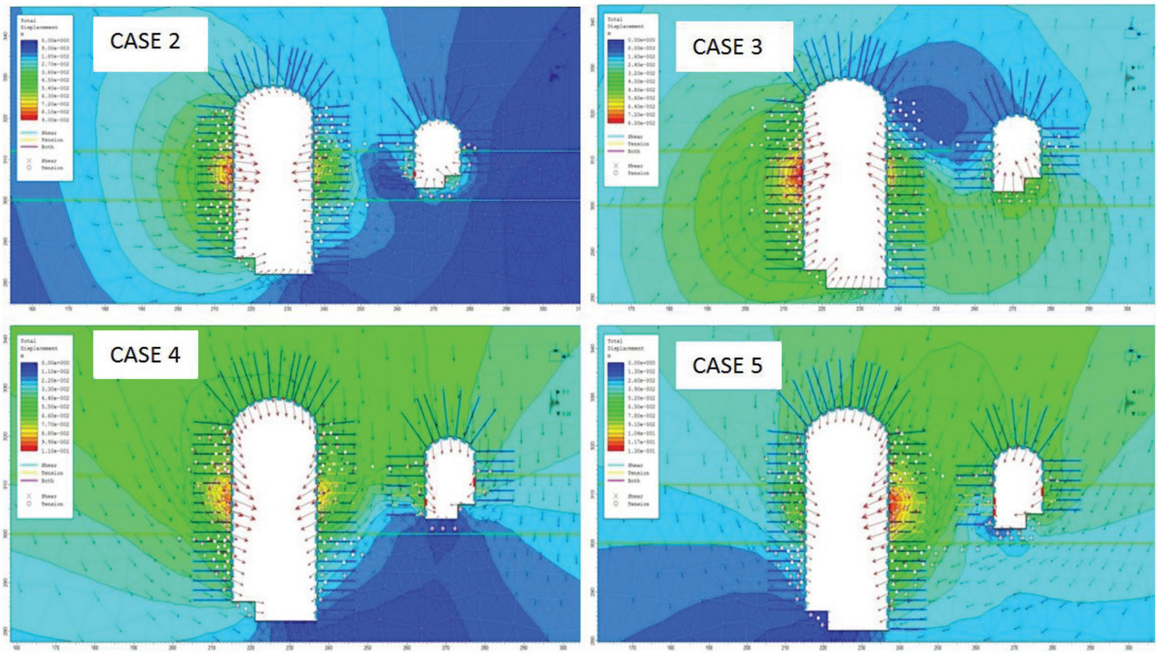
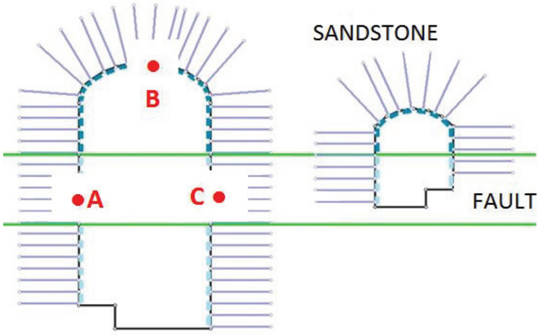
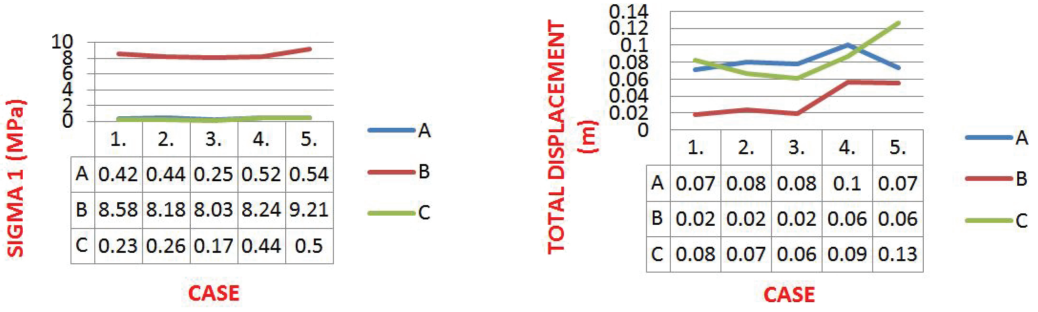


Figure 5: *Maximum calculated displacement versus different seismic coefficients combination and their directions for four CASES (2 to 5).*



Case number	Seismic coefficient
1.	$K_h = 0.0$, $K_v = 0.0$
2.	$K_h = 0.30$, $K_v = 0.0$
3.	$K_h = 0.30$, $K_v = 0.24$
4.	$K_h = 0.30$, $K_v = -0.24$
5.	$K_h = -0.30$, $K_v = -0.24$



	1.	2.	3.	4.	5.
A	0.42	0.44	0.25	0.52	0.54
B	8.58	8.18	8.03	8.24	9.21
C	0.23	0.26	0.17	0.44	0.5

	1.	2.	3.	4.	5.
A	0.07	0.08	0.08	0.1	0.07
B	0.02	0.02	0.02	0.06	0.06
C	0.08	0.07	0.06	0.09	0.13

Figure 6: *Combination of seismic coefficients and three analyzed points A, B, C.*

Conclusion from the above findings shows that a vertical seismic coefficient K_v = 0.5 kh is always applied in downward (negative) direction for all parametric analysis using pseudo-static seismic loading on underground structures. If for example use K_h = 0.30, representing a horizontal PGA at tunnel depth of 0.30 g, the K_v = 0.50/0.30 = 0.15. Assuming 0.70 as the reduction factor from surface to 100 m depth, surface PGA is ca. 0.30/0.7 = 0.43 g.

Natural containment

Today many options for designing nuclear power plants are available with the use of underground cavern and tunnel construction. It is evident that in any chosen design for such underground construction, cost savings can be materialized following the reduction of manmade containment structures typically required for an aboveground nuclear power plant. Thus are relying on the natural containment by the rock mass and the ground water. Reactor containment structures for current power plant designs are typically built in one of two ways. One option for a containment structure is a pre-stressed reinforced concrete shell with an interior steel liner which serves primarily as an impermeable membrane. A second option is a high integrity steel vessel that serves for containment with an independent concrete building around the vessel for shielding purposes[7]. Containment structures are typically designed to with-stand an interior pressure of four to five bars above atmospheric pressure.

Containment of an underground reactor could be significantly simplified compared to both surface and above ground solutions. Using the underground method of construction, no strong concrete structures are needed because the host rock surrounding a reactor serves the dual roles of shielding and providing the structural integrity of a containment structure as a natural barrier. In this basis of proposed technical solution, a containment structure for an underground nuclear reactor could consist of simply a thin steel liner supported by the host rock[1]. The steel liner would serve as an impermeable membrane between the reactor and the rock. This approach would eliminate the significant costs associated with construction of high-integrity steel structures which are needed in the above ground cases.

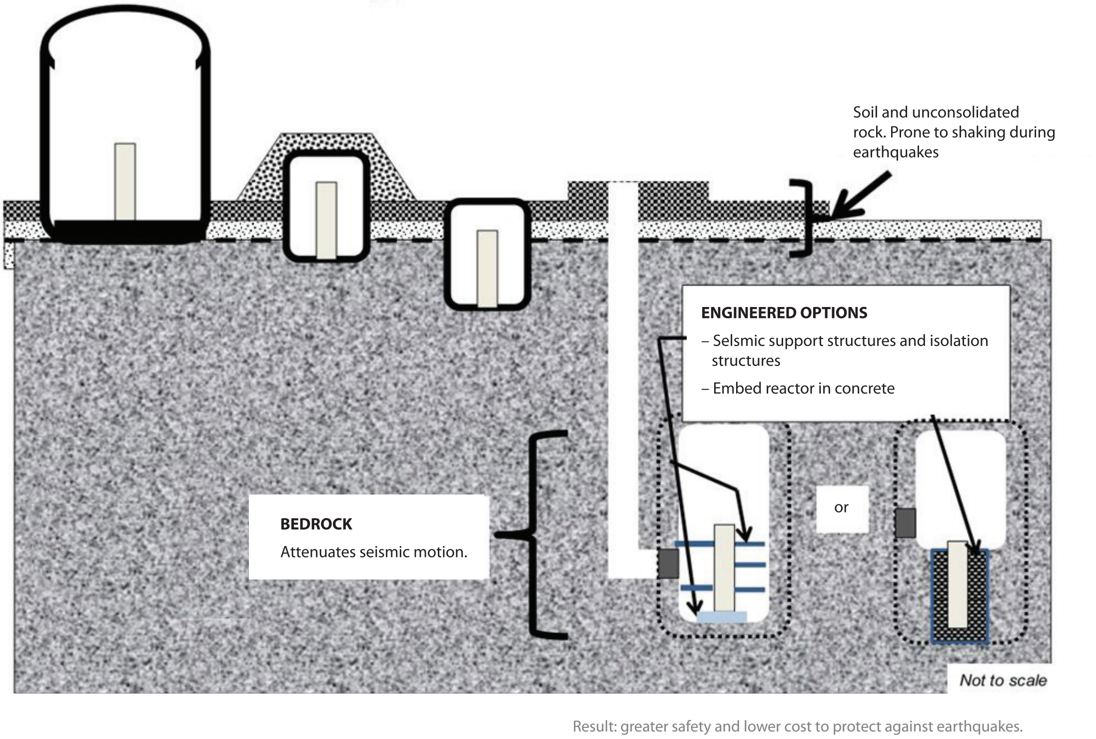


Figure 7: *Improved earthquake resistance*[1].

Geometrical bases of underground nuclear power plant (unpp)

In the present case all excavation are proposed with use drill and blast. Table 3 gives a preliminary cost estimate. The starting point for the concept shown in Figure 8 is with the dimensions and excavation cost for the shafts and tunnels and chambers for the reactor and turbine-generators for a 1 000 MW PWR in an underground nuclear park in granite[8]. This was done to arrive at a conservative preliminary estimate of excavation cost.

The main shaft is 24 m in diameter. It is excavated first to provide personnel and equipment access for all subsequent excavation operations.

After construction, the reactor pressure vessel, turbine-generators and other equipment would be transported down the main shaft to the main cavern. A secondary shaft, 12 m diameter, is constructed at the end of the main cavern opposite the main shaft and used for safety, ventilation and additional personnel and equipment access. The main cavern is 15 m wide × 15 m high × 120 m long, giving it a volume (27 000 m^3) approximately one-third the volume of the main cavern (77 000 m^3) for a 1 000 MW PWR reactor[8]. This is considered reasonable because the steam generator for the PWR is a large separate component, but for the reference SMR it is smaller and inside the pressure vessel. In addition, the turbine-generator chamber portion of the main cavern is 15 m high × 15 m wide × 40 m long.

This represents a reduction in height by about two-thirds and reduction in length by about one-half, the logic being less chamber space

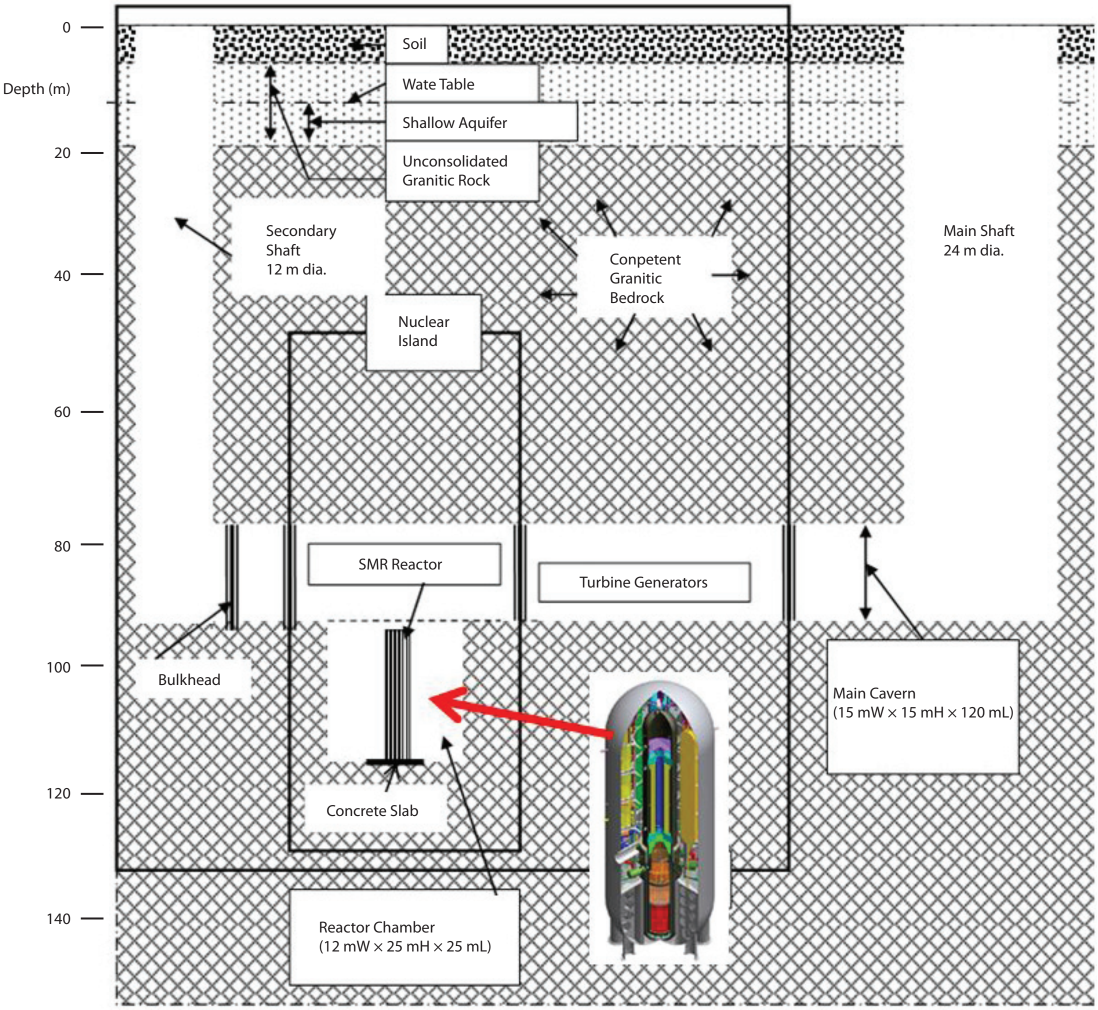


Figure 8: *Geometrical base for underground nuclear power plant – SINGLE UNIT, (C.W. Myers and J. M. Mahar, adapted Likar[9]).*

for turbine-generators should be needed for a 100–300 MW SMR, for example, than for a 1 000 MW PWR. The reactor chamber is 12 m wide × 25 m high × 25 m long, and lined with nominal concrete and steel or filled with concrete (not shown) to bring the SMR in intimate contact with the host rock depending on the seismic design requirements. The 25 m length of the reactor chamber, combined with having its long axis parallel to the long axis of the main cavern, provides space to rotate the SMR pressure vessel from its horizontal position during transport through the main cavern to its final vertical position in the reactor chamber. Once in position, the SMR would have an annular space for inspection, maintenance and other uses of 10 m on either side of the pressure vessel, parallel to the long axis of the main cavern.

Underground openings for a condenser and spent fuel storage pool are not shown on Figure 8, but to be conservative their excavation costs are included on Table 3. Also, cooling towers are not shown but it can recognize that they might be needed for water-cooled SMRs. The elevation difference between the ground surface and underground condenser will be an important topic relating to cost and engineering consideration. Under the definition the nuclear island encloses safety-class structures, systems and components: the reactor pressure vessel, reactor chamber, bulkheads sealing entrances to the reactor chamber, and the natural (host rock) containment structure.

In the case of bedrock SMR, the nuclear island would include those portions of the host rock surrounding the reactor chamber for which containment credit is taken. The nuclear island is shown schematically in Figure 8 with lateral boundaries passing through the two bulkheads nearest the reactor chamber. The nuclear island has a lower boundary at 130 m depth, and upper boundary at 50 m depth. Penetrations into the host rock containment structure should be controlled, the same as with a surface containment structure. The nuclear island is shown as a rectangle but in reality its shape would be dependent on site-specific geological, hydrological, and rock mass conditions, and would therefore be expected to have a more irregular shape. Four leak-tight bulkheads are shown.

Two isolate the turbine-generator chamber from the main shaft and from the reactor chamber and two others isolate the 12 m shaft from the reactor chamber. The two bulkheads adjacent to the reactor chamber must provide containment in the event of a reactor accident and are therefore safety class. On Figure 8, the rectangular outline shown as the unit cell encloses the chambers, tunnel, and shaft needed to operate a single underground SMR. Usage of the term follows Giraud[10] and is analogous to use of unit cell in crystallography, which refers to the way a crystal structure is created by repeating a pattern of atoms. A multiple reactor installation based on the unit cell in Figure 8 can be thought of as created similarly by repeating the unit cell pattern of the underground workings. Note that the unit cell shown in Figure 8 does not include the main shaft but it does include the 12 m diameter shaft. The primary purpose of the main shaft is to provide subsurface access during excavation and for transport of the

Table 3: *Preliminary Excavation Cost Estimates*

Shafts	Nominal Dimensions (m)	Volume (m^3)	Cost million €
Main Shaft	24 m (dia), 90 m (deep)	/	47.3
Secondary Shaft	12 m (dia), 90 m (deep)	/	15.7
		SUB TOTAL	**63.0**
Main Cavern	W = 15 m , H = 15 m, L = 120 m	27 000	2.2
Reactor, Chamber	W = 12 m, H = 25 m, L = 25 m	7 500	5.4
Condenser	22 m × 27 m × 30 m	17 800	1.1
Spent Fuel Pool	13.7 m × 24 m × 43 m	14 200	0.9
		SUB TOTAL	**9.6**
		TOTAL	**72.6**

Excavation cost of main shaft, secondary shaft, condenser, and spent fuel pool are from (Mahar et al. 2007, adapted Likar[9]). Unit cost of main cavern excavation is 81.5 €/m^3. Unit cost of reactor chamber excavation is 720 €/m^3.

reactor pressure vessel and other large equipment. After construction it would be available for other purposes including construction of subsequent SMR installations. In the case of horizontal opening with tunnel or similar horizontal connection, the shaft construction is not necessary.

Single-unit installation-drill and blast - construction procedure

As shown in Table 3, the cost per-reactor for single-unit bedrock SMR installation is approximately € 72.0 million, the price of the main shaft is approximately € 47.3 million, is by far the largest cost component. The 12 m shaft is € 15.7 million and all other excavations total only € 9.0 million. This estimates include ground support and internals in the shafts needed during excavation, but not cost to grout the bedrock if needed, construct the bulkheads, or any of the internals (platforms or stairways, for example) within the reactor chamber (Figure 9).

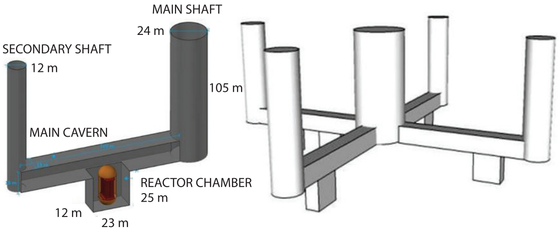


Figure 9: *Single and four unit installation, (Giraud[10], adapted Likar[9]).*

Four-unit installation-drill and blast - construction procedure

The concept for the four-unit installation is to build in series four of the unit cells shown in Figure 9 at the same depth, and have them positioned orthogonally around the main shaft. This allows the € 47.2 million cost of the main shaft to be shared among four SMRs. By doing this the per-reactor cost drops to € 35.4 million for the fourth reactor. It should be possible for the first reactor to be in operation while excavation is underway for the second, and similarly for subsequent reactors. Following the logic described for the staggered build of IRIS reactors, this approach also has the potential to reduce the capital at risk and cash outflow relative to conventional large, light water reactor construction.

Twelve-unit installation - tunnel boring machine construction

The first concept for a twelve-unit facility would be to adapt for bedrock SMRs siting the approach described by Giraud[10], based on earlier work by Mahar et al.[11], which uses tunnel boring machine (TBM) technology to construct an underground nuclear park with twelve, scale 1 000 MW, PWR reactors.

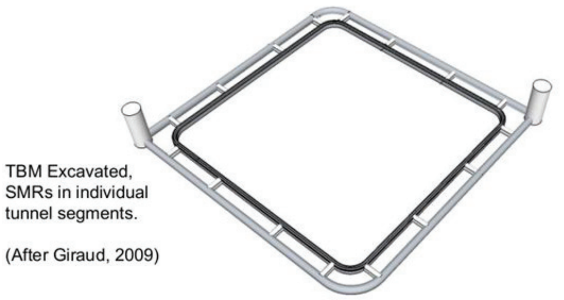


Figure 10: *Twelve unit installation[10].*

The underground facility has a total length 2 400 m, square-shaped footprint, with three power plants in each of its 600 m long sides. The total excavation cost of the TBM tunnel, secondary access tunnels and all shafts is estimated at € 236 million[10], or € 19.7 million per reactor location.

Although not in individually excavated chambers, as with the single- and four-unit concepts described above, each reactor and its turbine generator is isolated from all others by airlock/ bulkheads, reducing inter-reactor accident and investment risk. A second concept for a twelve-unit facility would be to site multiple SMR reactors together in a common chamber(s). Assuming TBM excavation technology is used as described in the preceding paragraph, and assuming because of more efficient use of space the twelve SMRs could be sited in a facility with an excavated length one-half as long, i.e., 1 200 m long, and assuming the excavation would cost ≈ 60 % as much, then the total excavation cost would be € 141.7 million and the per-reactor cost about € 11.8 million. From Figure 11 can see the individual unit cells are located around the perimeter, while access tunnels are located at the upper right and lower left.

Cost advantages for underground nuclear power parks

In addition to nuclear catastrophe in Fukushima today are the enormous investment costs associated with the construction of nuclear power plants has traditionally been the greatest economic limiting factor for the expansion of nuclear power. Nuclear power plants that are planned to be built in the United States have had a wide variety of projected construction costs. Progress Energy recently contracted with Westinghouse to build two AP1000 reactors in Florida at a total cost of € 6.0 billion. With the need for substantial additional transmission infrastructure, plus financing and other fees, Progress expects the entire project to cost approximately € 11.0 billion (U.S. Congress, 1989). This amounts to between 2 755 €/kW and 4 959 €/kW of installed capacity, depending on the elements covered in the costs. Other nuclear power plants applying for combined construction and operating licenses are estimating construction costs as low as 1 967 €/kW (U.S. Congress, 1989). Such wide variation in cost estimates is in part the result of recent substantial variations in material costs of concrete, steel, and copper. Because of the high capital costs associated with nuclear power plants, it is reasonable for those in the nuclear industry to be skeptical of a plan to complicate the construction process in any way, such as by placing plants underground.

However, it is likely that underground construction could actually be an overall economically advantageous endeavor for power plant owners. Building nuclear power plants underground can bring cost savings for construction in a variety of ways. Various options for the construction of power plants underground can be considered. One of them is cost savings which can be realized in the construction of containment structures. In addition, savings could be realized by reducing the overall volume of the reactor components due to enhanced emergency core cooling capability. Another advantage of underground reactors in rock is that they face far less seismic vulnerability and therefore need not be built with as strict seismic isolation requirements as surface plants. All of these

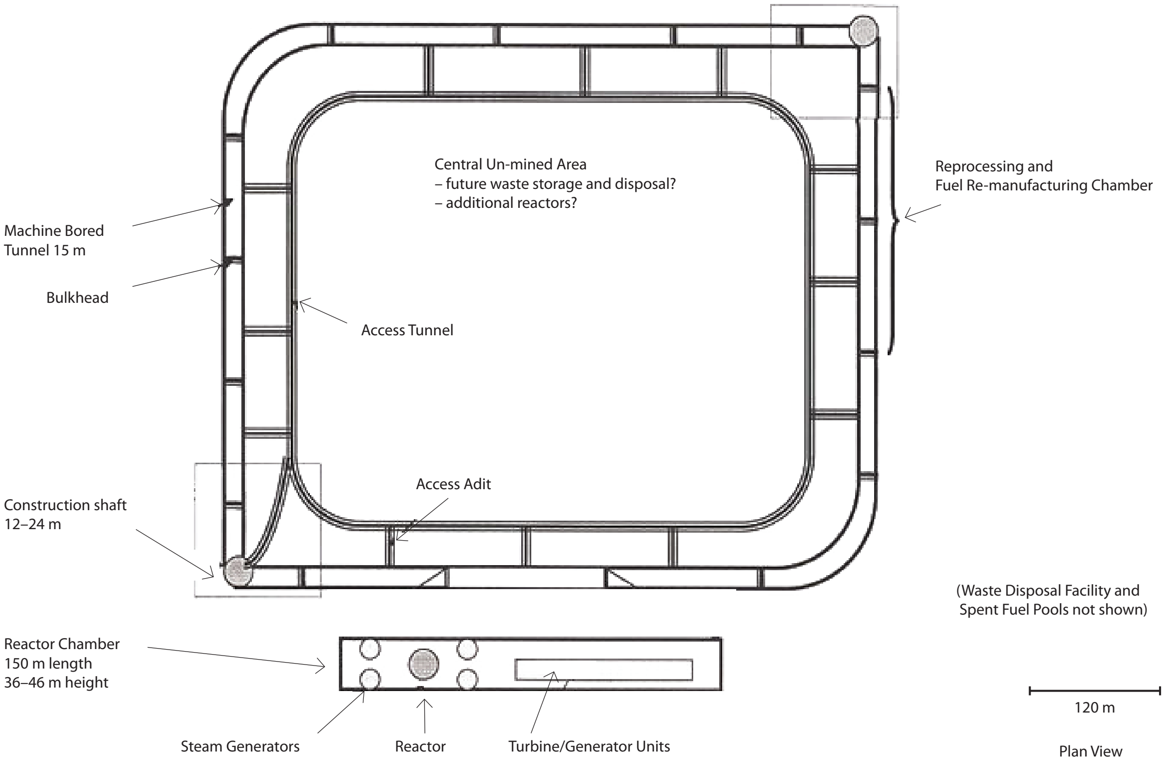


Figure 11: *A simplified schematic of an underground nuclear power park*[10].

factors combine to potentially reduce construction costs significantly. Construction cost savings for underground nuclear power plants are highly dependent on the ingenuity involved in designing the plant, enhanced Emergency Core Cooling Capability. This is because the large compartment for storing emergency cooling water within the containment above conventional reactors would not be necessary, as more than adequate water storage would be available above ground should emergency core cooling be needed. From this point of view nuclear power plant building close to existing hydro plant has many advantages, because cooling water is available in big amounts.

Construction of reactors underground allows for a variety of options in placing the various components of the nuclear power plant. The tunneling technology has long existed to excavate a large enough volume of underground space to place reactors as they are currently designed. For example, the AP 1 000 containment building is a cylinder with a height of 83 m and a diameter of 40 m. The ABWR containment building has a height of 30 m and a diameter of 30 m. These recent designs, involving large heights for the containment structures, are the result of the efforts to incorporate passive emergency core cooling capabilities into the designs, using gravity feed for the emergency core water. Such considerations pale in significance when reactors are placed underground because the emergency core cooling water can be placed at the ground surface. Thus, gravity driven water pressure can be provided from water reservoir on the surface which existed for hydro power plant that would be 10 bar or more (for depths of 100 m or more). Such emergency core cooling capacities (virtually unlimited) and large pressure heads warrant complete reconsideration of emergency core cooling passive designs. Thus, while it is possible to excavate a volume of rock comparable to the space for current containment buildings, the abundance of host rock and the greatly enhanced passive core cooling capability offer a number of innovative ways of placing the major components of a nuclear steam supply system. For example, PWRs constructed underground would not need to have the steam generators and the pressure vessel all in the same compartment. By separating components of the system in adjacent compartments a more efficient use of the underground space can be achieved.

Conclusions

Underground structures suffer appreciably less damage than surface structures in situations when subject to earthquake loading. Reported damage decreases with increasing overburden or depth of location. Deep tunnels are safer and less vulnerable to earthquake loading than shallow underground structures.

Most of the damage locations coincide with reactivating existing faults and fracture zones, but these can be identified before and/or during construction whilst conducting adequate investigations. Severe damage and collapse of tunnels from shaking occur only under extreme conditions. Usually damage due to shaking is rare in underground facilities. Where such damage has occurred, the rock is either very poor or subject to very high stresses and the lining has bad quality (i.e. brick or unreinforced liners).

Earthquake experience shows that most damage occurs to the tunnel liner, and such damage is well correlated with its quality of construction. Support measures holding a sufficient ductility would absorb the vibrations from an earthquake and maintain its supportive function despite surface damage such as cracking.

No damage or minor damage can be expected in rock tunnels for peak ground acceleration at the ground surface less than about 0.2–0.4 g, depending on type of lining and rock mass conditions.

Existing underground hydropower plants being located in favorable quality rock mass would also constitute suitable bedrock for a SMR sitting in the goal to produce high capacity of electricity at the lowest possible. That possibility is still open to start with activities very soon. In additional such test and demonstration facilities for prototype SMRs should be done to start within the regions without risk of damage from military attack or earthquakes.

Where bedrock conditions would be adequate for sitting SMRs, the solution with underground nuclear power plant is economic and environmental friendly. The main advantage is in using existing transmission grid and transportation infrastructure. Whilst certain benefits related to investigations is present from the results of original hydropower plant and existing workforce expertise in power generation and distribution.

In the safety domain high margins of safety and physical protection against accidents and external threats are achieved by underground citing. Integration of nuclear and hydropower plants has potential benefit in the environmental restoration process.

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