



혁신형SMR기술개발사업단
Innovative SMR Development Agency

최신 연구활용 원자로계통 설계기술 워크숍

모듈러원전의 내진/면진설계 연구개발 현황

서 춘 교

한국전력기술 원전기술연구소 구조내진연구팀

KNS 추계학술발표회, 2025.10.29.

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Innovative SMR Development Agency

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- 부지배치 및 최우선 요건
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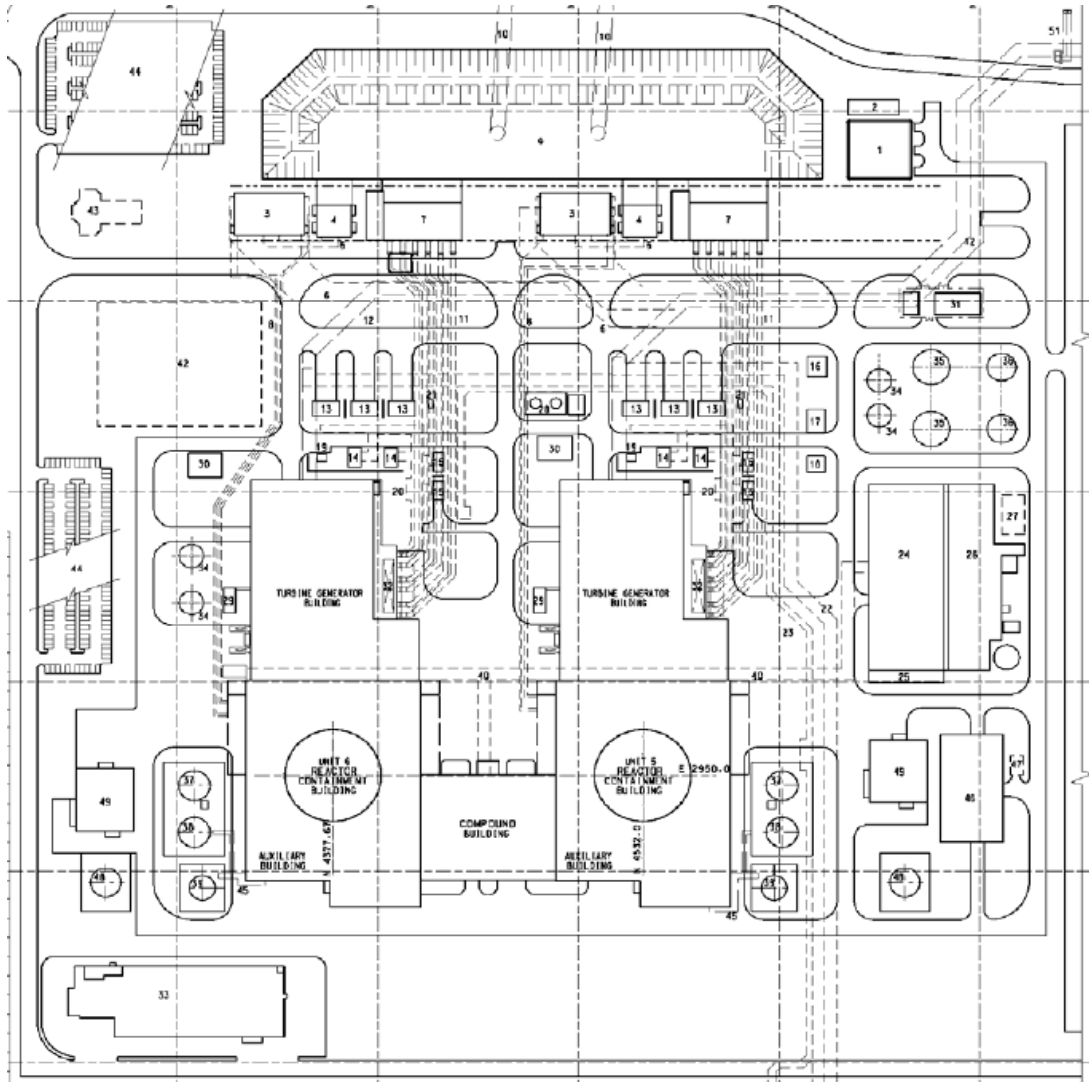
Q&A

PART I

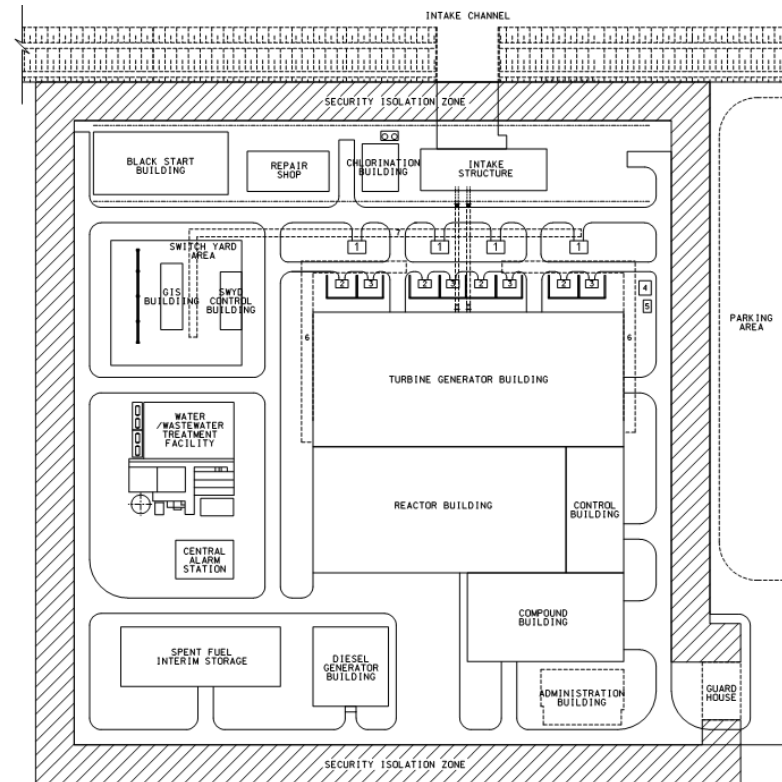
혁신형 SMR 내진설계 현황

- 일반사항 (GA)
- 내진설계 변수
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< 새울 3&4 >



< 혁신형 SMR(안) >



◆ SMR 파워블럭

➤ 원자로보호건물

- 4개의 원자로모듈 배치
- 사용후 연료저장조 배치
- 원자로모듈 관련 기기 배치 등

➤ 제어건물

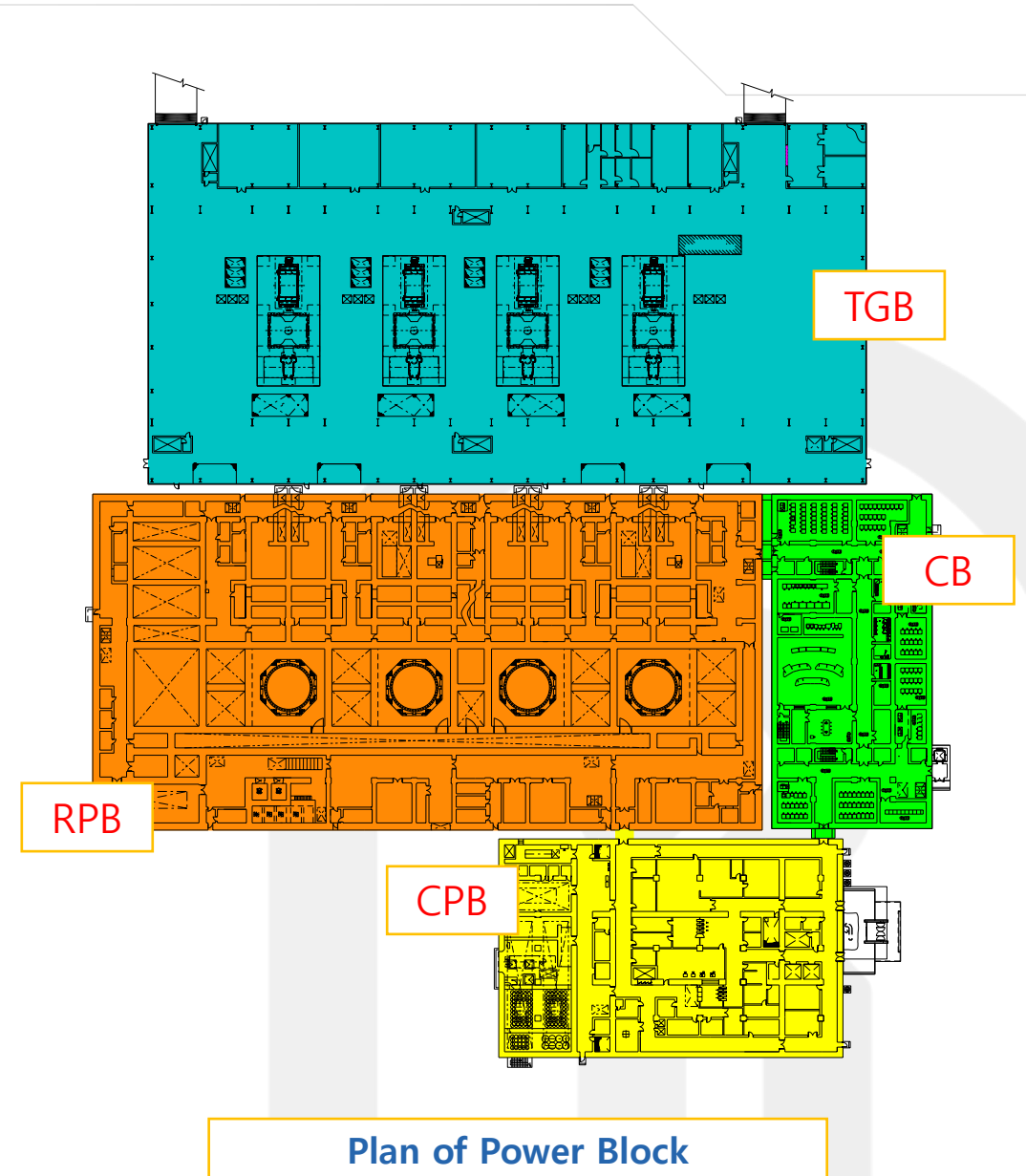
- 통합제어실 배치
- 비안전급 전기기기, 공조기기배치

➤ 복합건물

- 출입통제시설 설비
- 방사선폐기물 저장설비 등

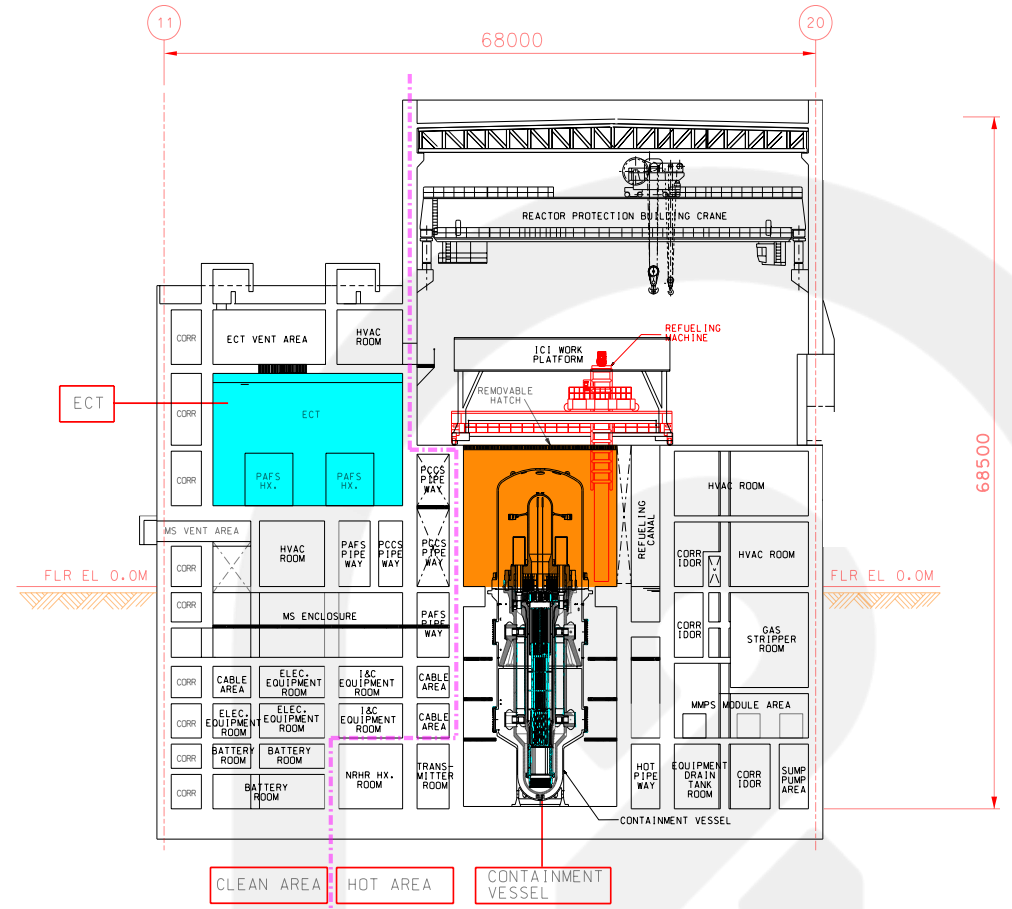
➤ 터빈건물

- 터빈발전기 (4대)
- 복수기 (4대) 및 기타설비



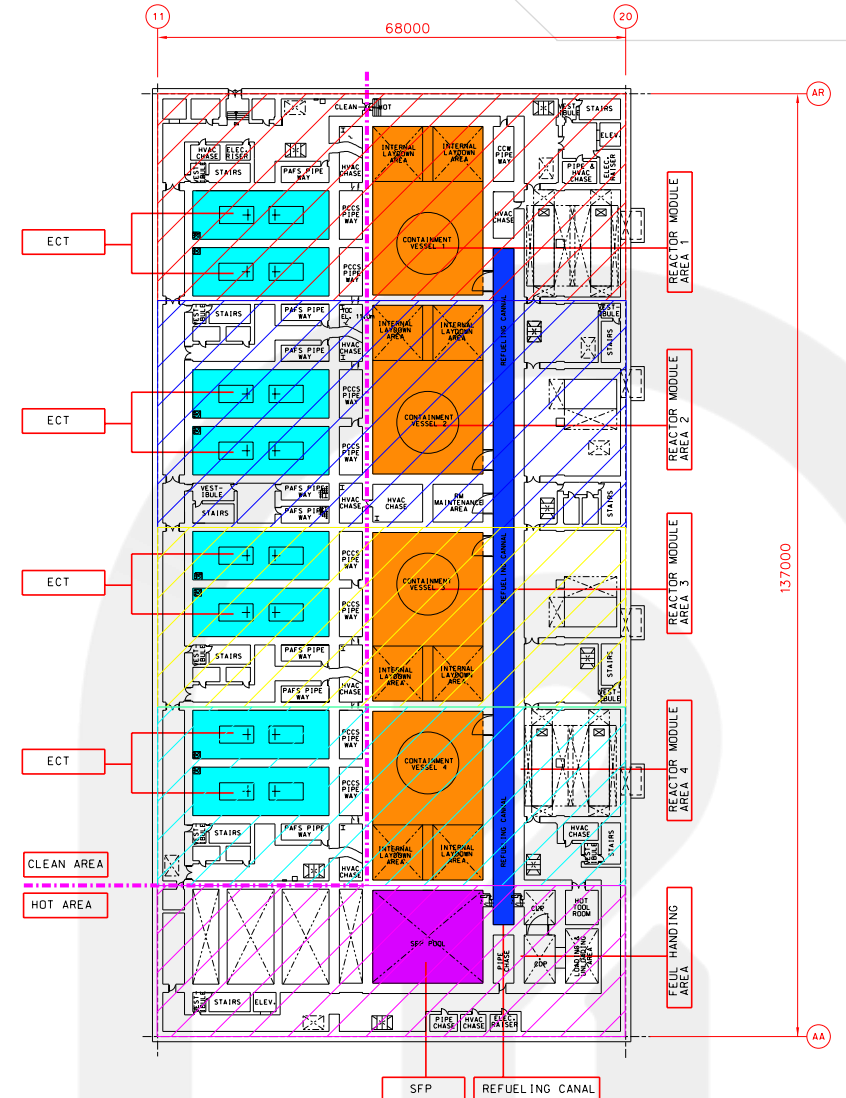
SMR 원자로보호건물 일반기기배치도 - 단면

- 크기 : 68m (폭) x 68.5 m (높이)
- 층고 결정 인자
 - 원자로모듈 및 철제 격납용기 크기 고려
 - 비상냉각탱크 (ECT) 용량 및 높이 요건 고려
- 지하 3 층 (바닥층 EL -22.0m)
 - EL -22.0m/ EL -15.0m / EL -7.0m (주요층)
 - EL-18.0m/EL -11.0m/ EL-3.5m (부분 중간층)
- 지상 3층 (방사성관리구역 기준)
 - EL 0.0 m / EL. 7.0m / EL14.0m (운전층)
 - 상부 CV 인양 고려
 - 원자로보호건물 크레인 배치



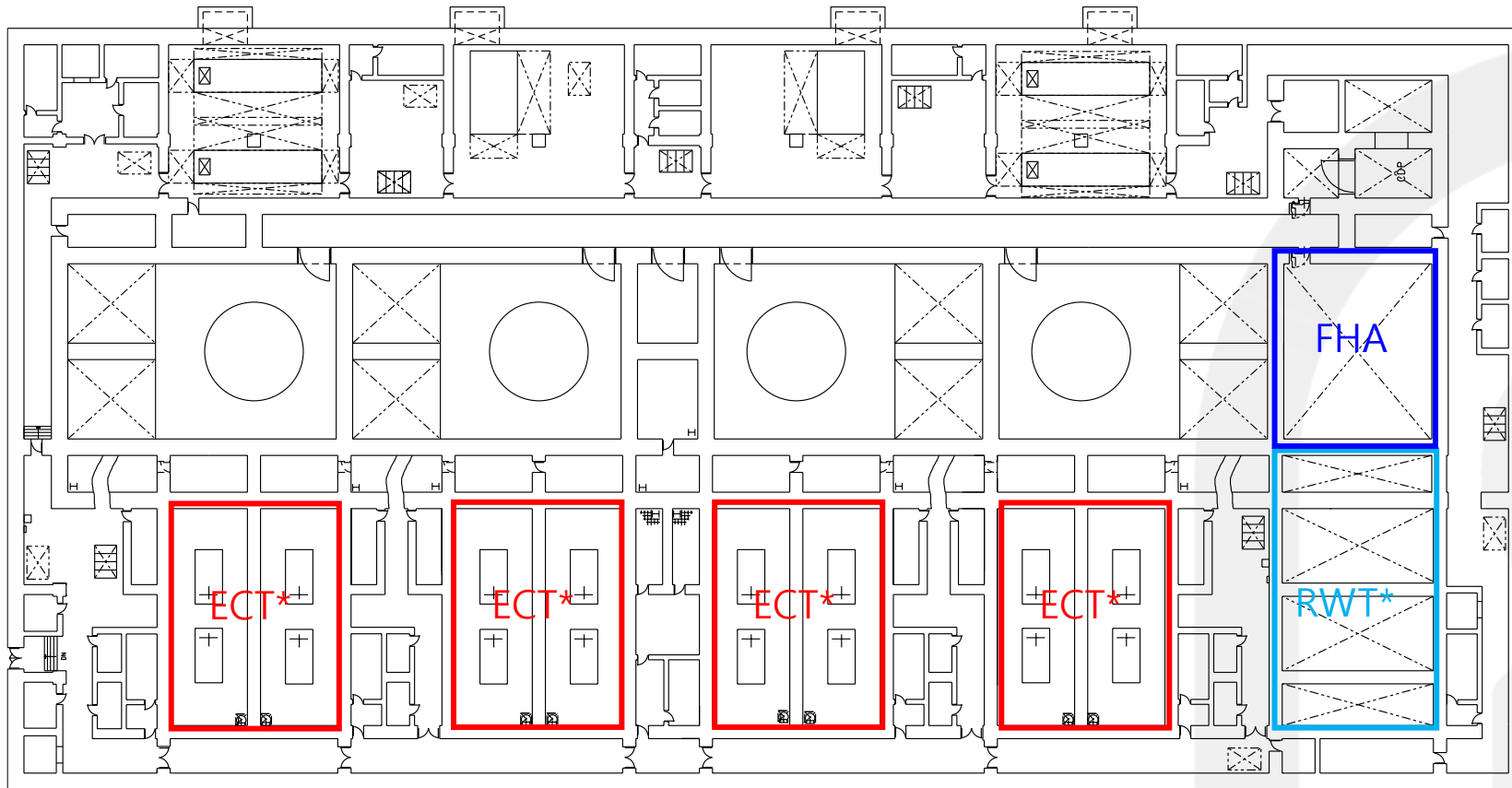
모듈지역 단면형상

- 크기 : 137 m x 68 m (평면)
- 4개의 원자로모듈 지역 및 연료취급구역으로 구분
 - 원자로 모듈별 배치 필요기기는 구역 내 배치
 - 공유배치 가능기기는 건물 내 분산 배치
- 사용후연료저장조 배치 (건물내 20년 습식저장 고려)
- 방사선구역 (Hot Area)
 - MMPS 모듈 및 관련기기 배치
 - 정상잔열제거계통 관련 기기
 - 관리구역 공조기기 배치
- 비방사성구역 (Clean Area)
 - 비상냉각탱크 (ECT) 및 피동안전계통(PCCS, PAFS) 연결배관
 - 원자로모듈과 연계한 안전급 계측기기 및 고신뢰도 축전지실
 - 주증기배관/급수배관 연결관로 (MS Endosure)



EL. 7.0m 지역

◆ SC구조 적용범위 (유체탱크)

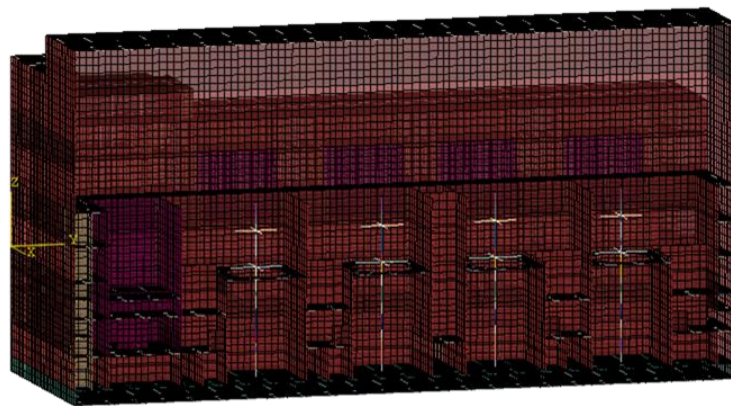
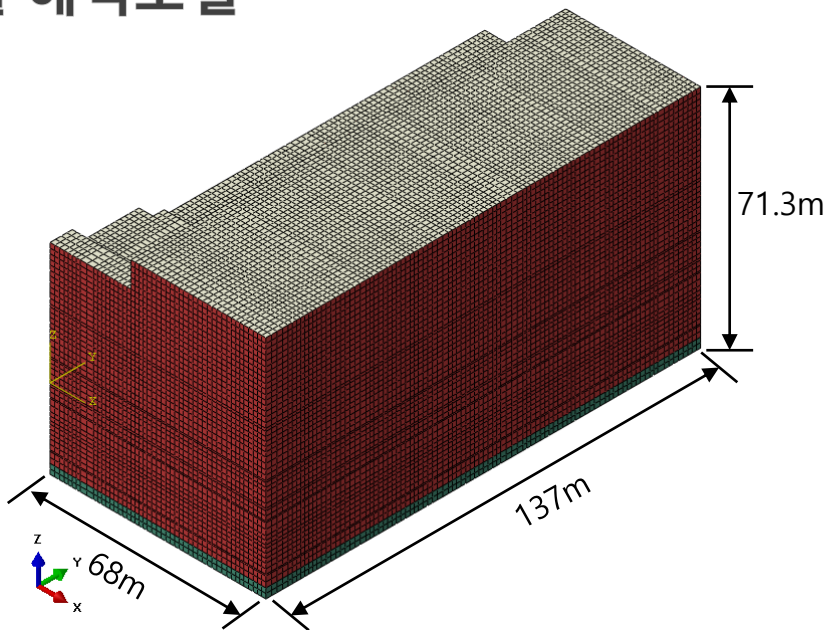


◆ 원자로보호건물 및 제어건물 해석모델

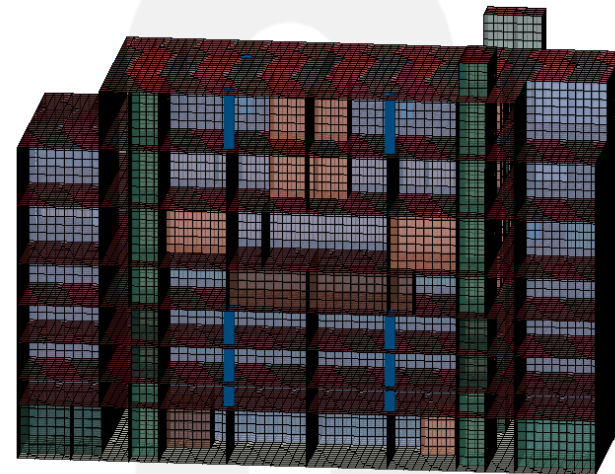
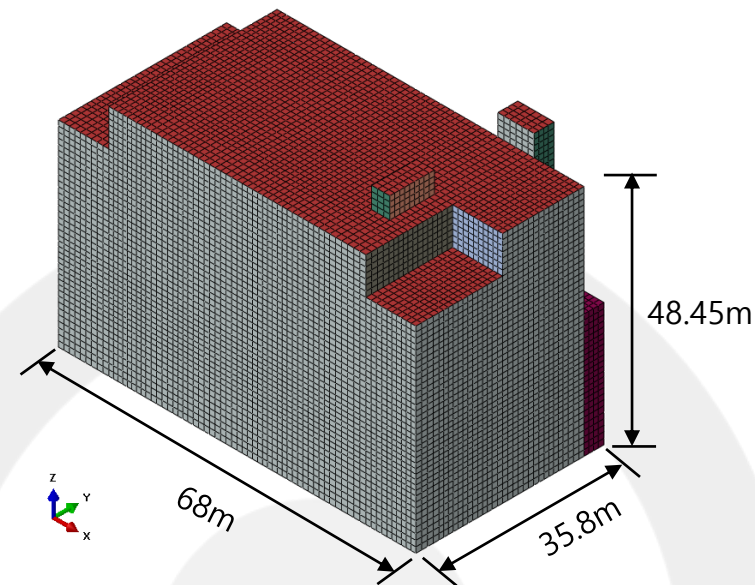
➤ 3차원 유한요소 모델

➤ 중량 정보

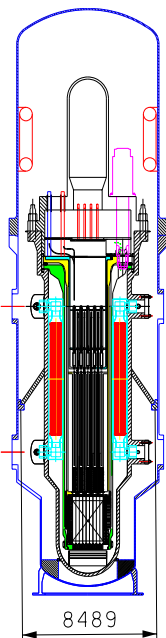
- RPB : 541,377 ton
- CB : 89,390 ton
- RV-CV 모듈 : 4,119 ton



RPB

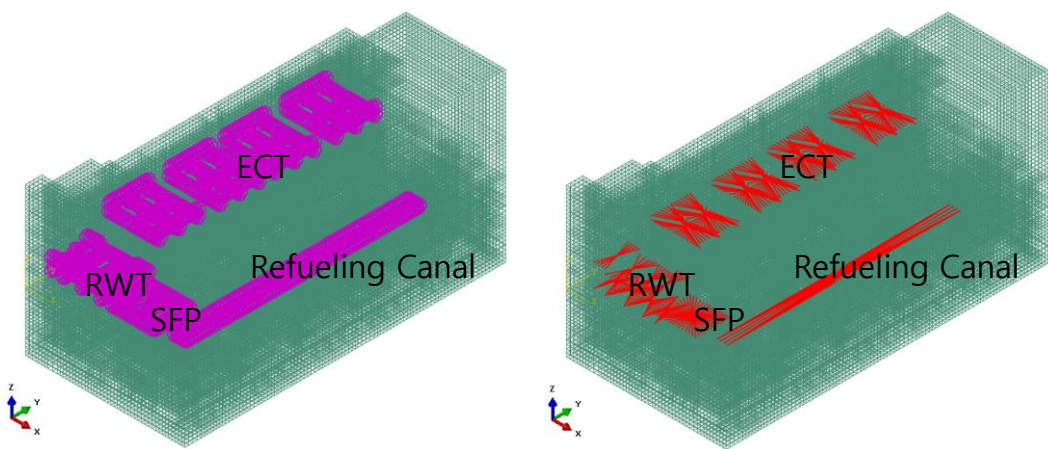


CB



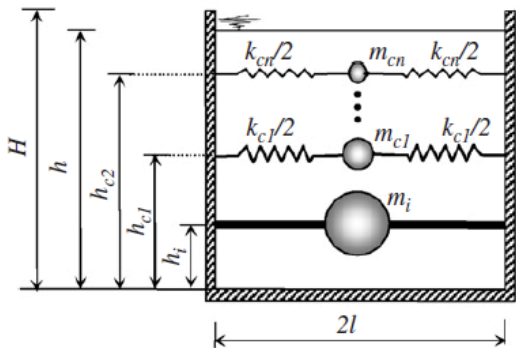
◆ 동수역학 모델

➢ 4개 유체탱크(SC 구조)에 적용



Convective component

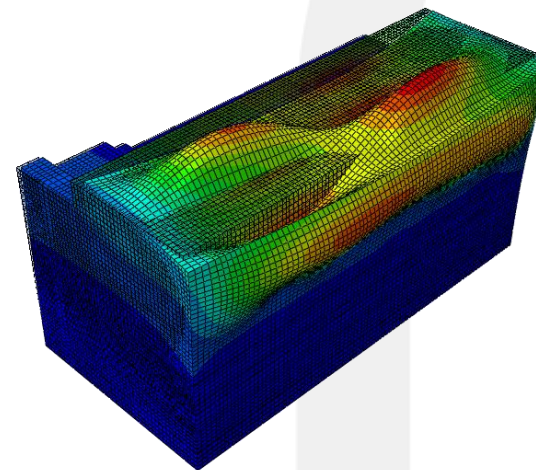
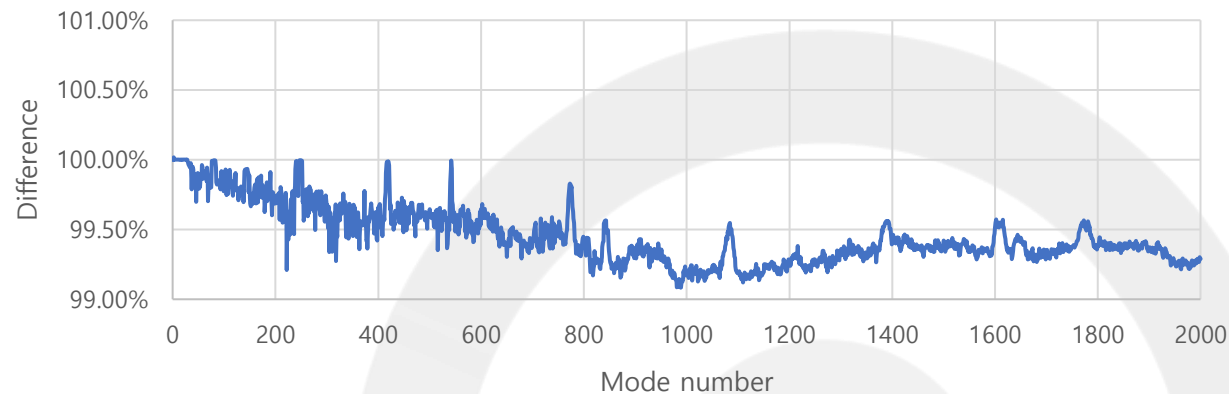
Impulsive component



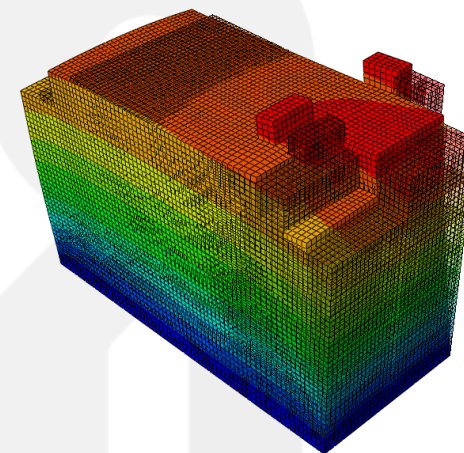
m_t is the total mass
 m_c is the convective mass
 m_i is the impulsive mass
 h is the depth of fluid
 h_{cn} is the height of convective mass
 h_i is the height of impulsive mass
 k_{cn} is the stiffness of the convective mass spring

◆ 고유진동수 비교

➢ 총 2000개 모드 비교 : 최대오차 0.98%



RPB X dir. 1st



CB X dir. 1st

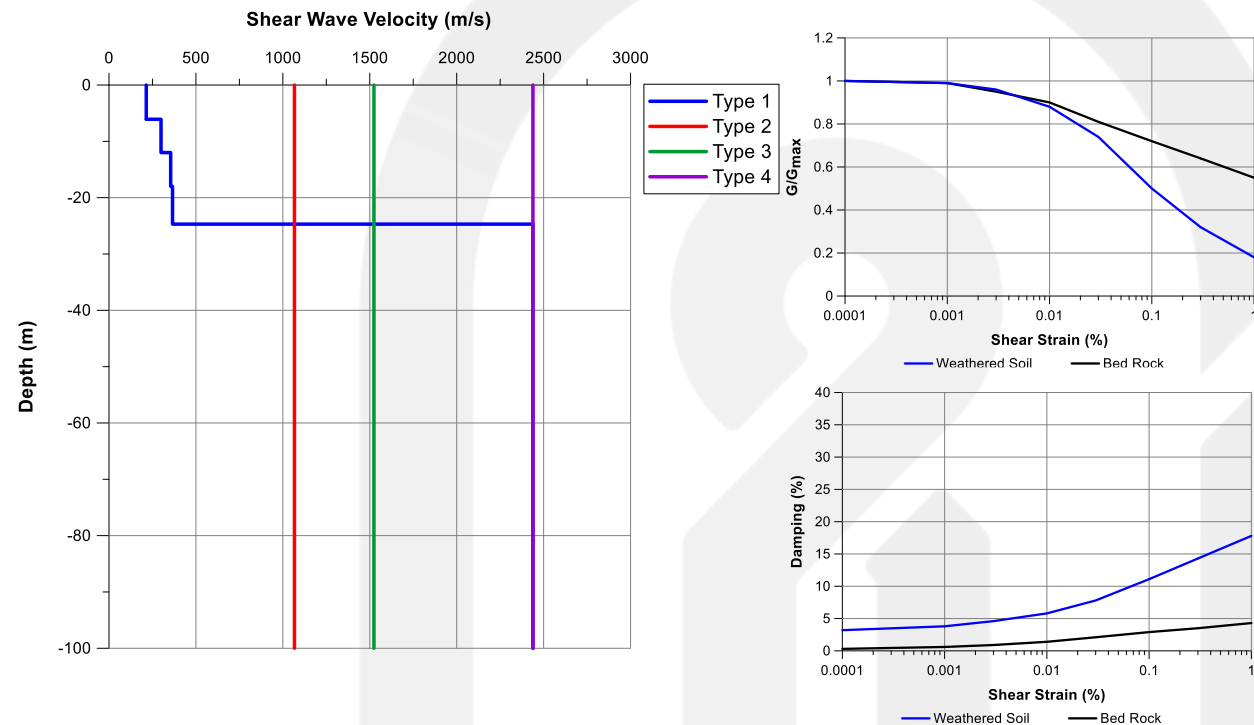
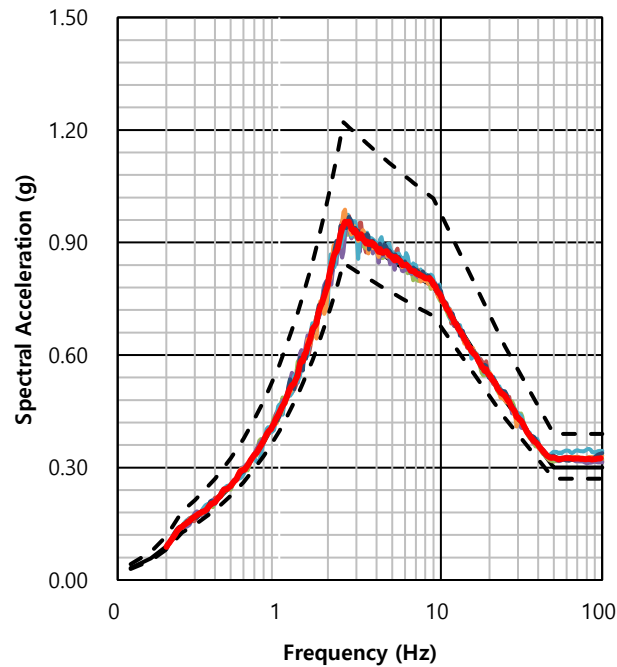
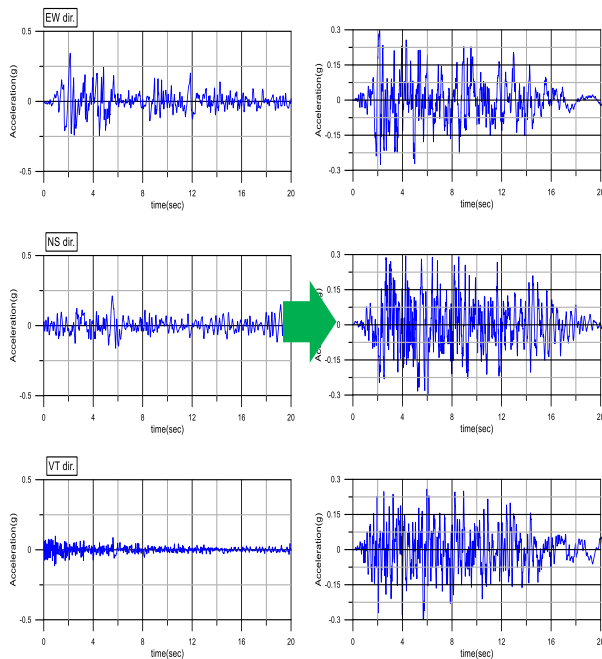
• Housner GW. Dynamic pressures on accelerated fluid containers. Bull Seism Soc Am 1957;47:15-35.

◆ 설계기반지진운동

- 설계기준지반응답스펙트럼(DGRS) $PGA = 0.3g$
- 실측지진파 기반 7개 세트의 인공지진파 작성
- SRP 3.7.1 Option 2 작성요건 모두 만족

◆ 포괄부지 지반조건

- 4개 부지조건 선정
- 지반 비선형성 고려 부지응답해석을 통한 등가선형 지반물성 결정

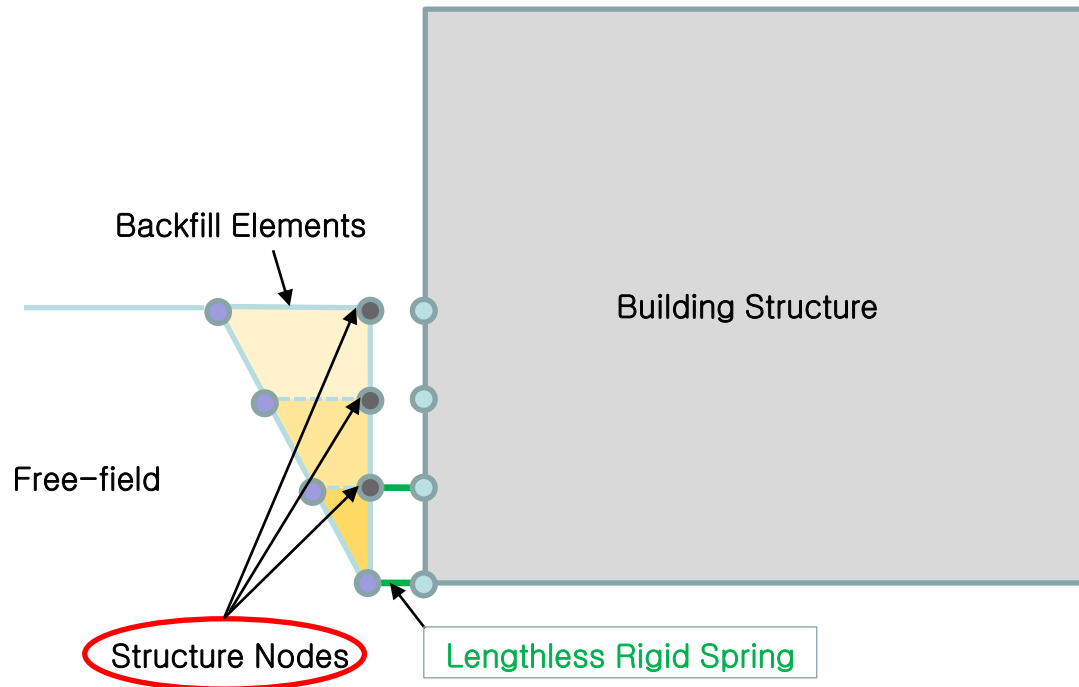


IV

내진설계변수 (2)

◆ 다양한 불확실성 고려

- 구조물 외벽과 측면지반(뒷채움) 간의 잠재적 접촉상실(절점 분리) 고려
- 콘크리트의 잠재적 균열 고려



◆ 내진설계변수 고려 해석종류

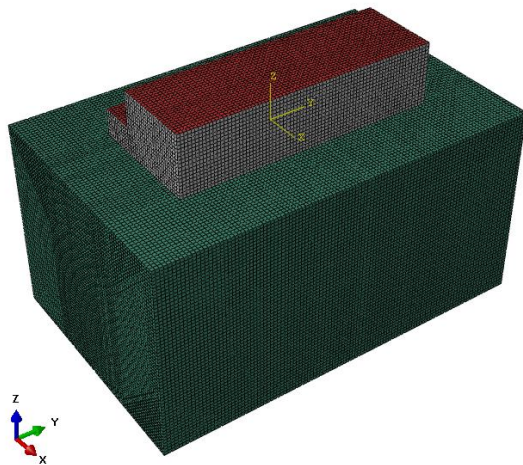
- 입력지진파(7), 부지조건(4), 접촉 상실(2), 균열 여부(2)
- 총 해석종류 : 226개

내진해석 변수	OBE (감쇠 4%, 비균열)	SSE* (감쇠 7%, 균열)	비고
입력지진파	7	7	
부지조건	4	4	NuScale Type1 반영
접촉상실	2	2	
구조물 (RPB, CB)	2	2	
해석 개수	112	112	
경사파 고려 (0°, 17°, 30°)		2	Soil Type-3 (Vs = 5000 ft/s)
총 해석 개수	226		

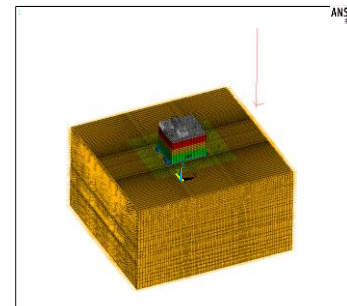
* SC 구조 : 6%

◆ SSI 해석법 : 직접법 (Direct Method)

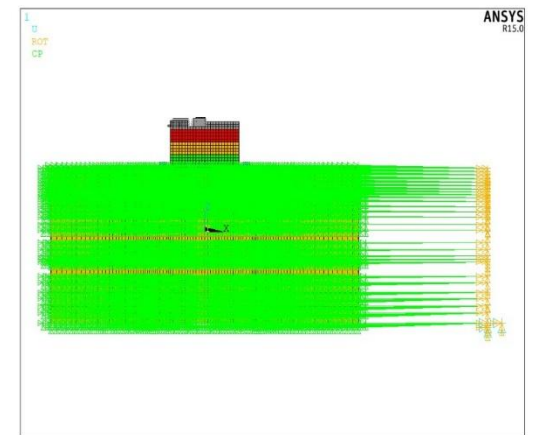
- 직접법은 구조물의 굴착범위에 종속되지 않으며, 구조물과 지반을 하나의 이산시스템에서 미지수 계산.
- 직접법의 강성행렬은 근역(구조물-지반)의 유한요소와 원역 지반의 인공경계(동적 무한요소, 전달경계요소, 흡수경계 등)가 직접 결합하여, 띠행렬 형태의 희소행렬로 구성. 고속처리 대수기법 적용 가능.
- 관련 해석 프로그램
 - **KIESSI-3D** for the Frequency Domain Analysis (NQA-1 SQA in Progress)
 - **ANSYS APDL** for the Transient Analysis in Time Domain qualified by NQA-1 SQA



i-SMR 원자로보호건물의 직접법 해석 모델 (진동수 영역)

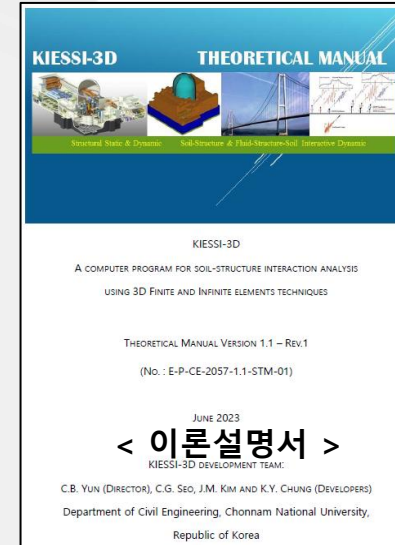
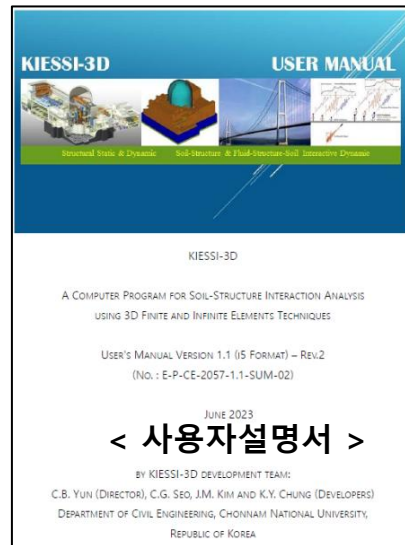
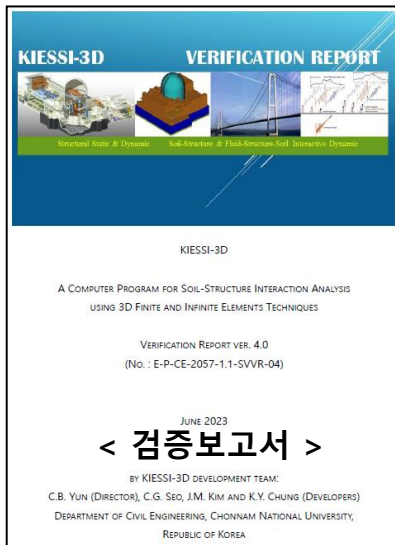


소내 비상대응거점의 직접법 해석 모델 (시간 영역)



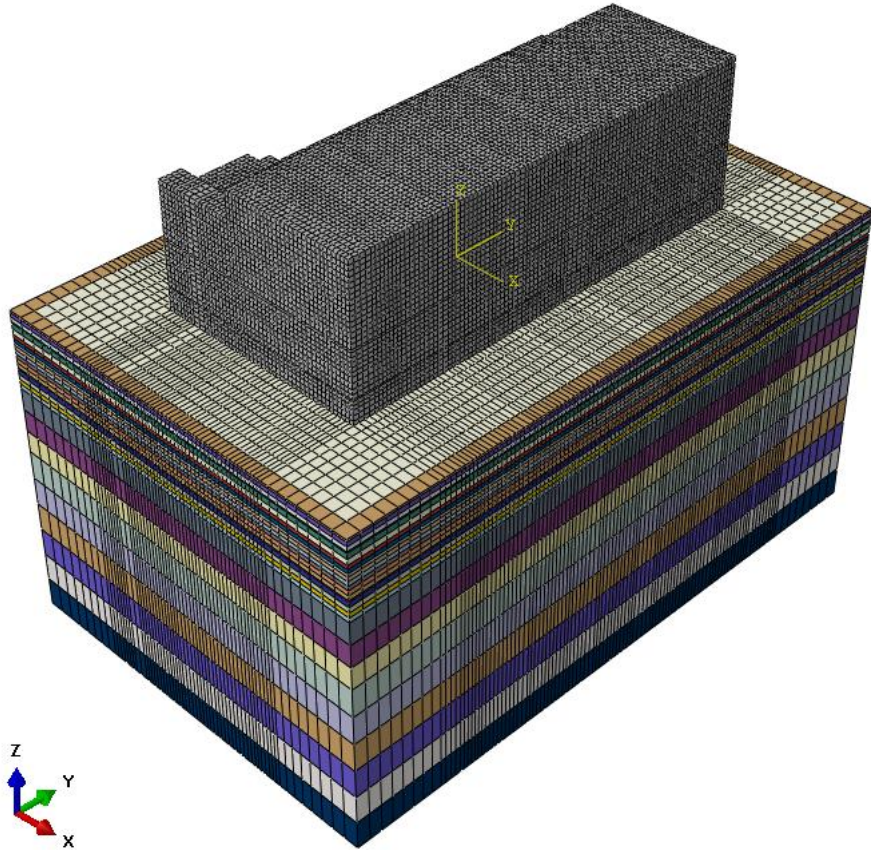
◆ KIESSI-3D 특징

- Soil-Structure Interaction Analysis Tool developed by Korean researchers under **KINS sponsorship (1993)**
- KIESSI program utilizes finite elements (FE) for modeling structure & near-field soil medium, and dynamic infinite elements (IE) for horizontally layered half-space.
- General Static/Dynamic problems in time & frequency domains
- **General SSI problem in frequency domain**

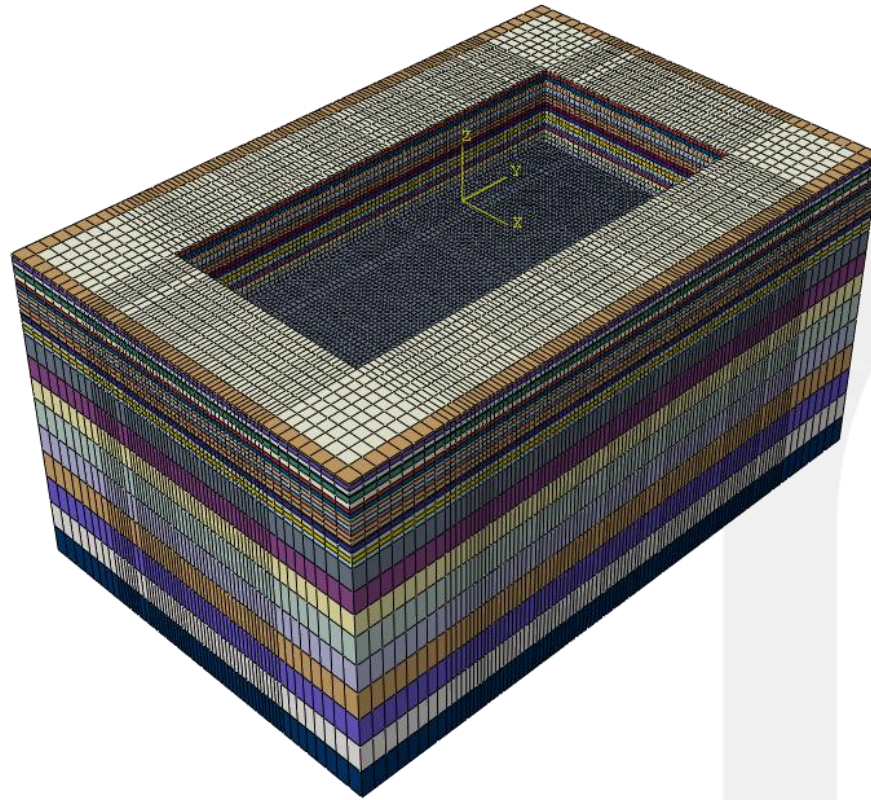


* ASME NQA-1 2008, 2009a 기반 소프트웨어품질보증(SQA) 절차 도입 및 적용중 (KESCOM: KNF iCODE 차용)

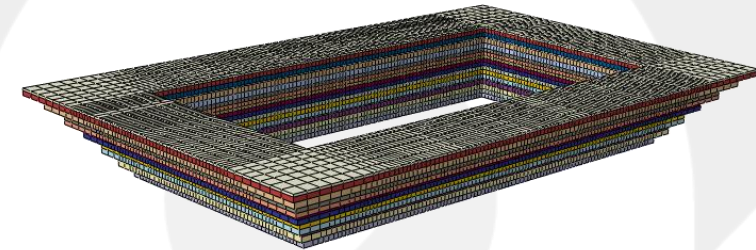
◆ KIESSI-3D 해석 모델 (RPB)



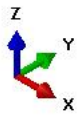
SSI 해석모델(Soil Type 4)



근역지반 해석모델(Soil Type 4)

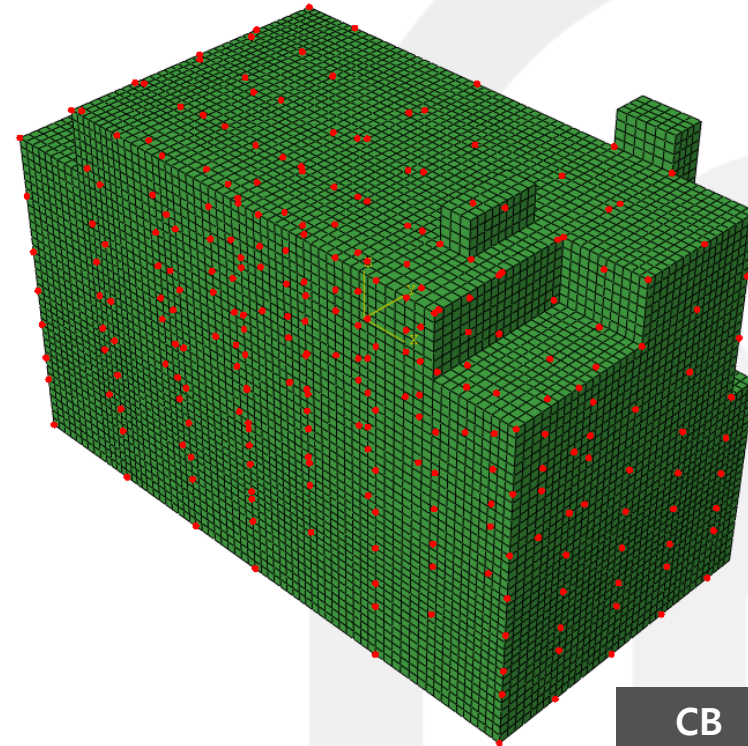
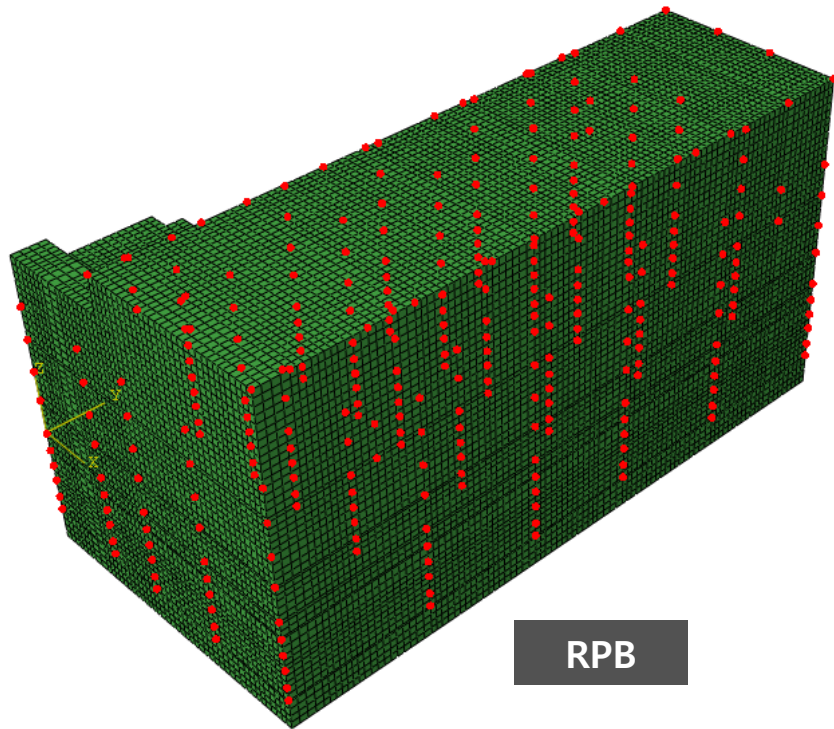


SFG (backfill)



◆ 구조물내응답스펙트럼(ISRS) 추출 위치

- RPB 출력 층 높이: -22m(bottom), -18.3m, -15.3m, -11.3m, -7.8m, -4.25m, -0.3m, 7.25m, 13.7m, 20.7m, 27.7m, 46.3m(top)
- CB 출력 층 높이: -23.75m(bottom), -17.3m, -14.3m, -9.8m, -5.3m, -0.3m, 6.7m, 13.7m, 20.7m



◆ 구조물내응답스펙트럼(ISRS) – Enveloped & Widened FRS of 56 SSE cases

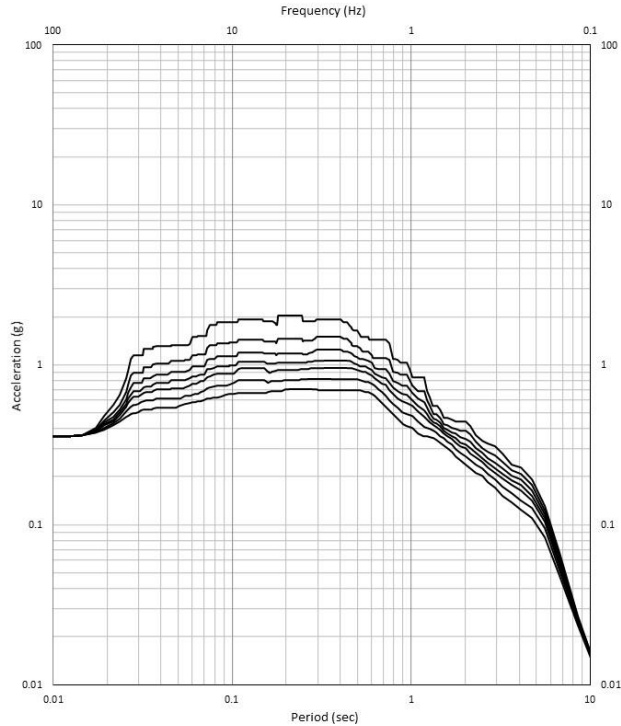
➤ 원자로보호건물 기초상부(GL-22.0m)



PROJECT : TDG28
CALC. NO. : C-CO-00001

FLOOR RESPONSE SPECTRA OF REACTOR PROTECT BUILDING
ISMR_RPB

SAFETY-RELATED
PEAK WIDENED ON EACH SIDE BY 15%
DAMPING : 1% 2% 3% 4% 5% 7% 10%



Node ENVELOPED
Direction E-W

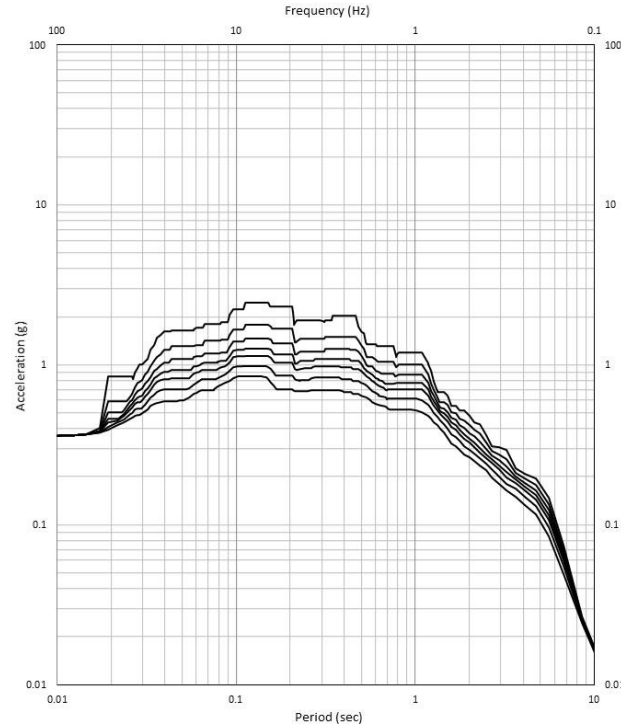
Spectra No. GL-22_0m-EW
Elevation -22.0m
Location RPB BASE



PROJECT : TDG28
CALC. NO. : C-CO-00001

FLOOR RESPONSE SPECTRA OF REACTOR PROTECT BUILDING
ISMR_RPB

SAFETY-RELATED
PEAK WIDENED ON EACH SIDE BY 15%
DAMPING : 1% 2% 3% 4% 5% 7% 10%



Node ENVELOPED
Direction N-S

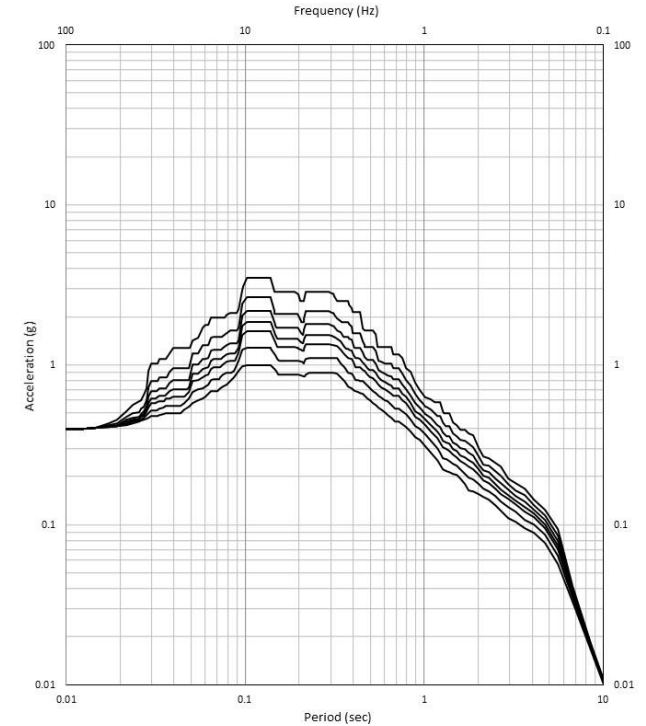
Spectra No. GL-22_0m-NS
Elevation -22.0m
Location RPB BASE



PROJECT : TDG28
CALC. NO. : C-CO-00001

FLOOR RESPONSE SPECTRA OF REACTOR PROTECT BUILDING
ISMR_RPB

SAFETY-RELATED
PEAK WIDENED ON EACH SIDE BY 15%
DAMPING : 1% 2% 3% 4% 5% 7% 10%



Node ENVELOPED
Direction VT

Spectra No. GL-22_0m-VT
Elevation -22.0m
Location RPB BASE

◆ 구조물내응답스펙트럼 (ISRS) – Enveloped & Widened FRS of 56 SSE cases

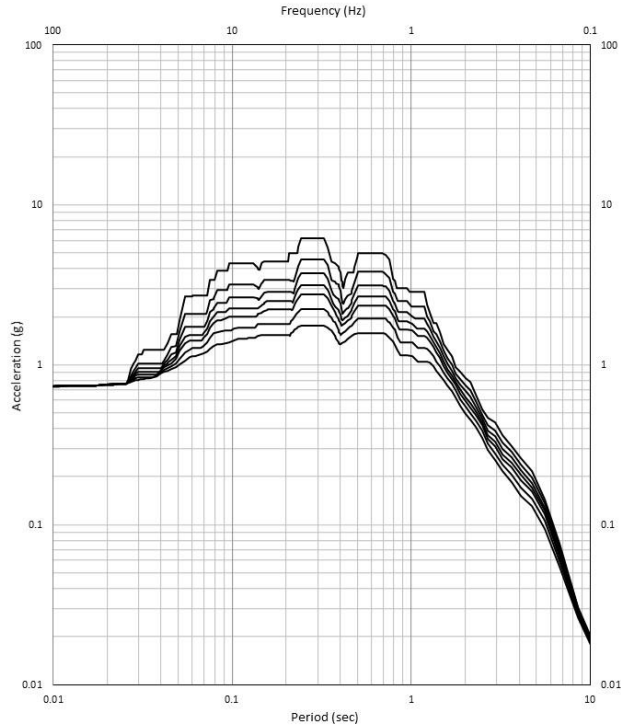
➤ 원자로보호건물 격납용기 결합층(GL-0.3m)



PROJECT : TDG28
CALC. NO. : C-CO-00001

FLOOR RESPONSE SPECTRA OF REACTOR PROTECT BUILDING
ISMR_RPB

SAFETY-RELATED
PEAK WIDENED ON EACH SIDE BY 15%
DAMPING : 1% 2% 3% 4% 5% 7% 10%



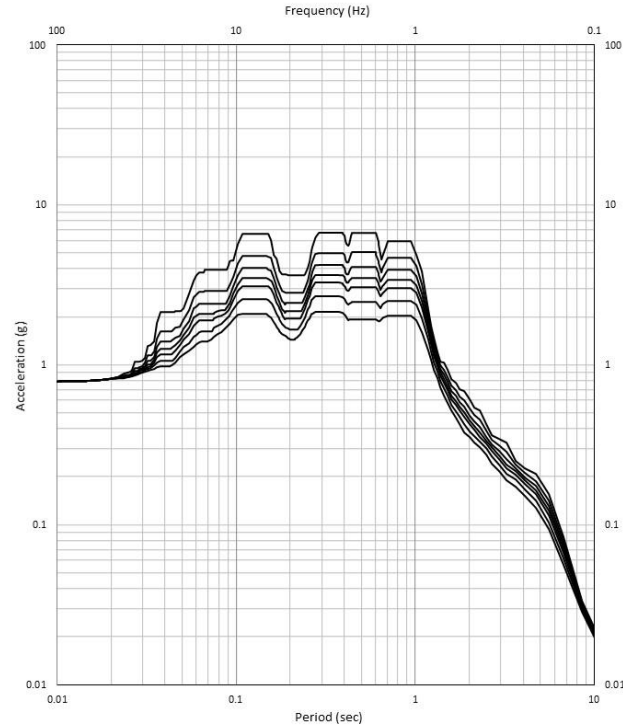
Node	ENVELOPED	Spectra No.	GL-0_3m-EW
Direction	E-W	Elevation	-0.3m
		Location	RPB WALL



PROJECT : TDG28
CALC. NO. : C-CO-00001

FLOOR RESPONSE SPECTRA OF REACTOR PROTECT BUILDING
ISMR_RPB

SAFETY-RELATED
PEAK WIDENED ON EACH SIDE BY 15%
DAMPING : 1% 2% 3% 4% 5% 7% 10%



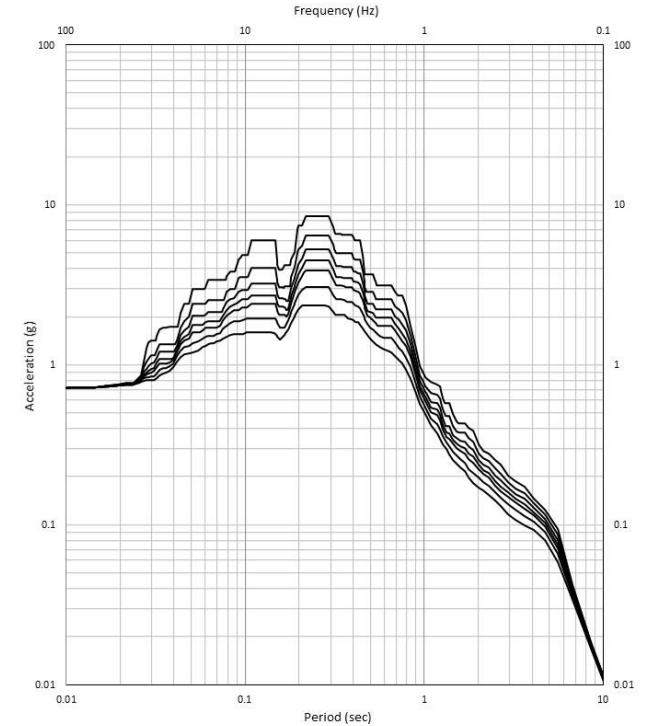
Node	ENVELOPED	Spectra No.	GL-0_3m-NS
Direction	N-S	Elevation	-0.3m
		Location	RPB WALL



PROJECT : TDG28
CALC. NO. : C-CO-00001

FLOOR RESPONSE SPECTRA OF REACTOR PROTECT BUILDING
ISMR_RPB

SAFETY-RELATED
PEAK WIDENED ON EACH SIDE BY 15%
DAMPING : 1% 2% 3% 4% 5% 7% 10%



Node	ENVELOPED	Spectra No.	GL-0_3m-VT
Direction	VT	Elevation	-0.3m
		Location	RPB WALL

◆ 구조물내응답스펙트럼 (ISRS) – Enveloped & Widened FRS of 56 SSE cases

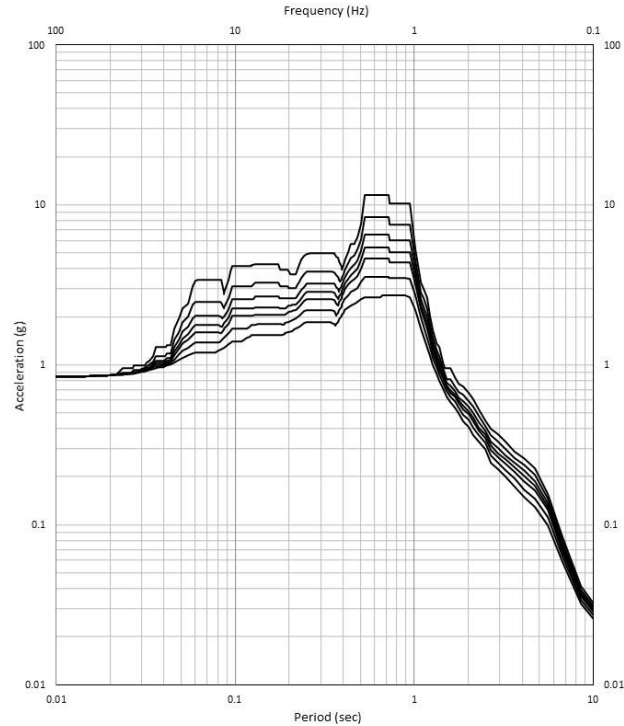
➤ 원자로보호건물 운전층 (GL+13.7m)



PROJECT : TDG28
CALC. NO. : C-CO-00001

FLOOR RESPONSE SPECTRA OF REACTOR PROTECT BUILDING
ISMR_RPB

SAFETY-RELATED
PEAK WIDENED ON EACH SIDE BY 15%
DAMPING : 1% 2% 3% 4% 5% 7% 10%



Node ENVELOPED
Direction E-W

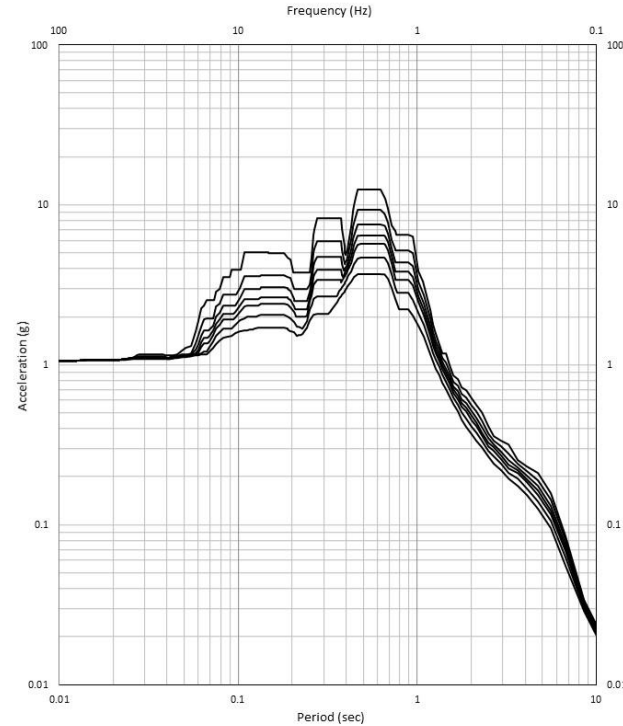
Spectra No. GL+13_7m-EW
Elevation 13.7m
Location RPB WALL



PROJECT : TDG28
CALC. NO. : C-CO-00001

FLOOR RESPONSE SPECTRA OF REACTOR PROTECT BUILDING
ISMR_RPB

SAFETY-RELATED
PEAK WIDENED ON EACH SIDE BY 15%
DAMPING : 1% 2% 3% 4% 5% 7% 10%



Node ENVELOPED
Direction N-S

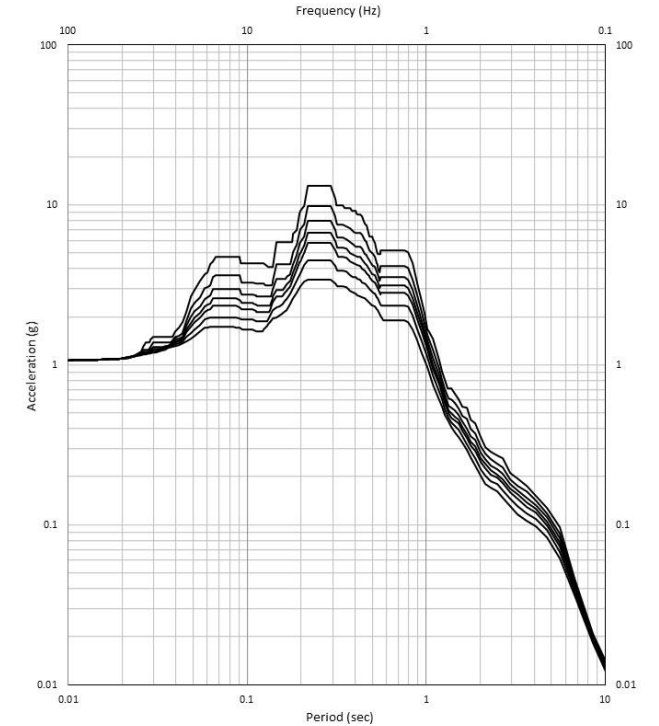
Spectra No. GL+13_7m-NS
Elevation 13.7m
Location RPB WALL



PROJECT : TDG28
CALC. NO. : C-CO-00001

FLOOR RESPONSE SPECTRA OF REACTOR PROTECT BUILDING
ISMR_RPB

SAFETY-RELATED
PEAK WIDENED ON EACH SIDE BY 15%
DAMPING : 1% 2% 3% 4% 5% 7% 10%

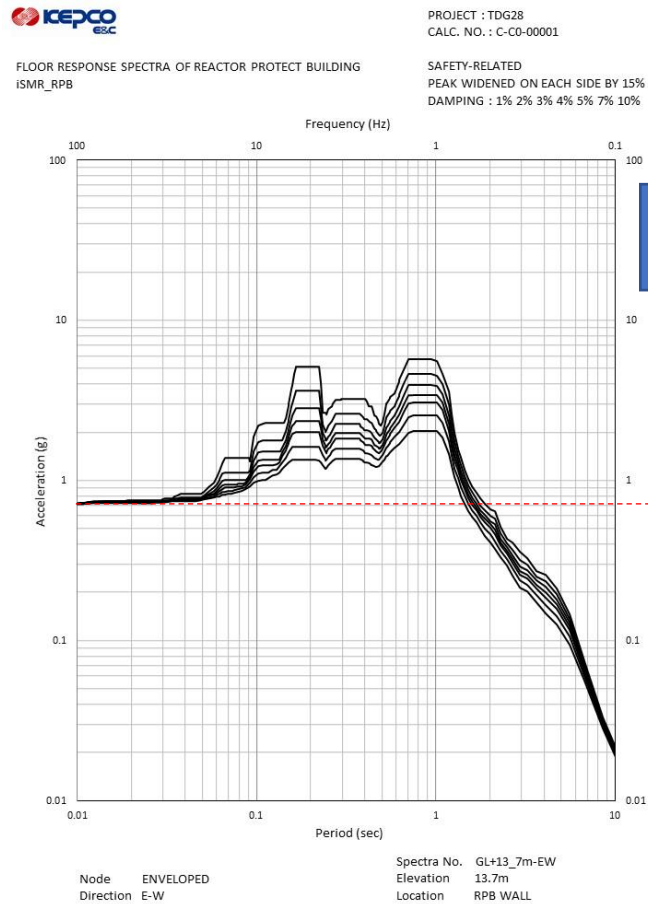


Node ENVELOPED
Direction VT

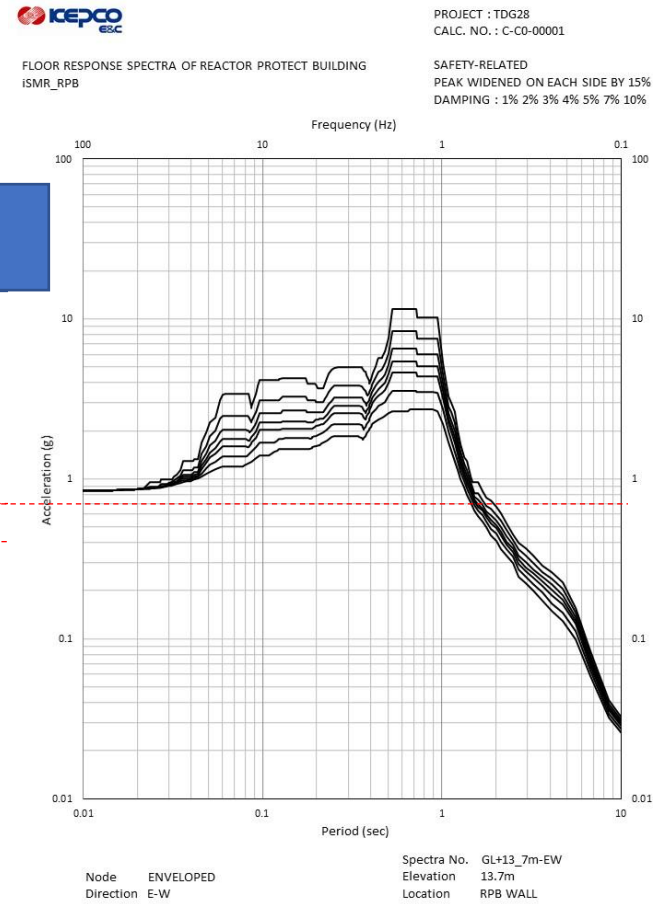
Spectra No. GL+13_7m-VT
Elevation 13.7m
Location RPB WALL

◆ 지진응답 비교

➤ 원자로보호건물 (고정기초해석 vs SSI 해석)



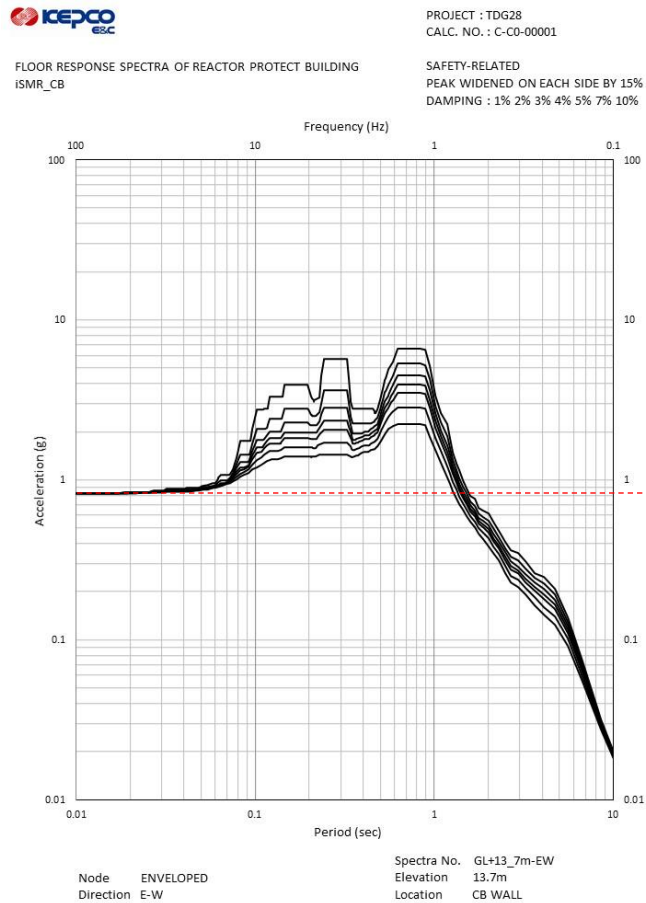
< 고정기초해석 >



< SSI해석 >

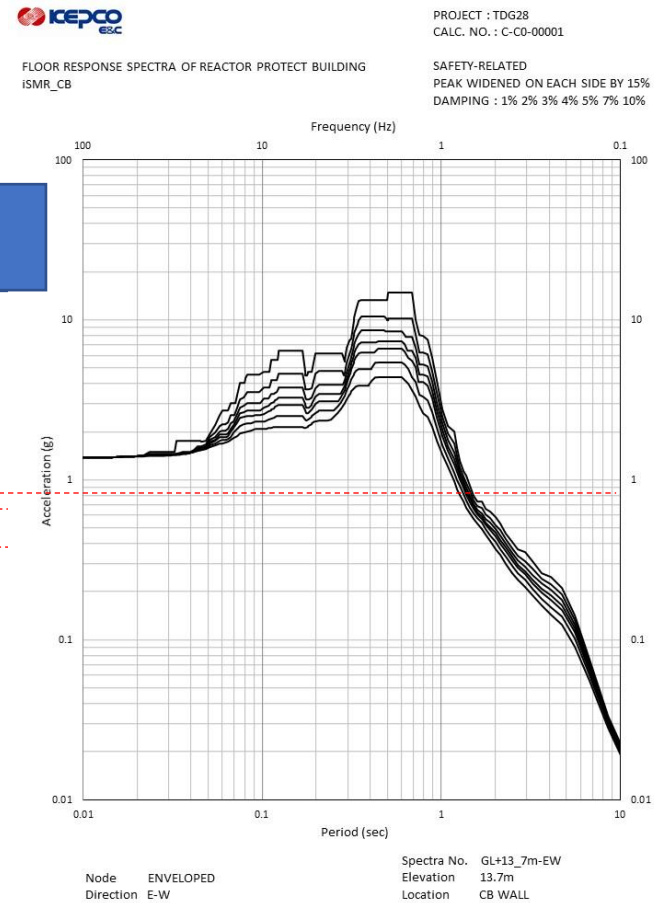
◆ 지진응답 비교

➤ 제어건물 (고정기초해석 vs SSI 해석)



< 고정기초해석 >

층슬래브
(GL 13.7m)



< SSI해석 >

◆ 지진응답 비교

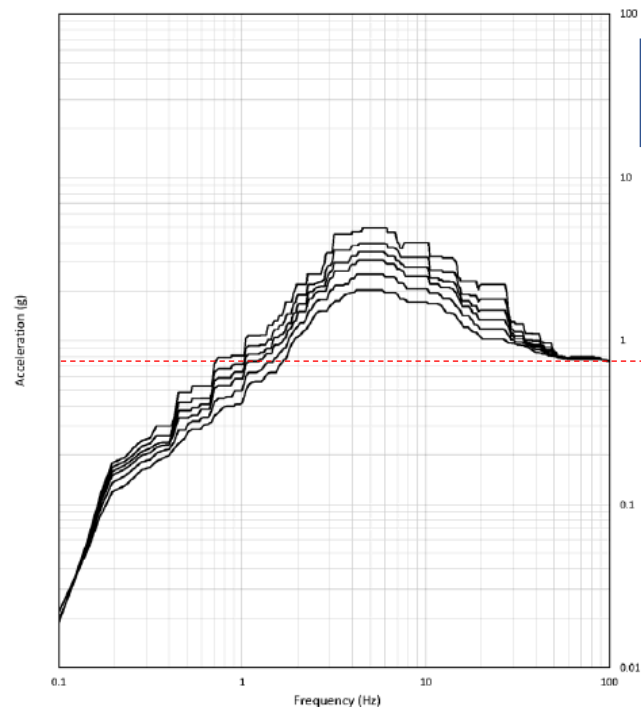
➤ SMART100 vs i-SMR



PROJECT : TDG28
CALC. NO. : C-CO-00001

FLOOR RESPONSE SPECTRA OF REACTOR PROTECT BUILDING
iSMR_RPB

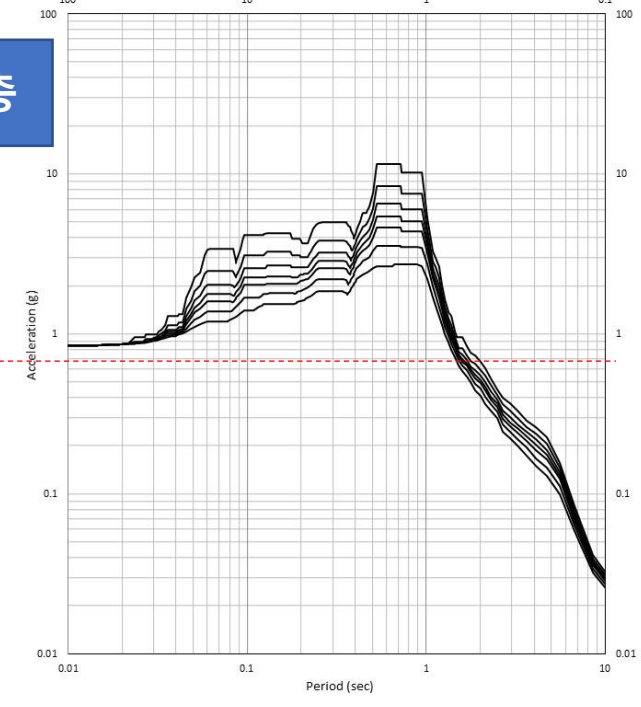
SAFETY-RELATED
PEAK WIDENED ON EACH SIDE BY 15%
DAMPING : 1% 2% 3% 4% 5% 7% 10%



Building	Reactor Containment and Auxiliary Building	Spectra No.	RCA-L7-01-EW-SSE
Location	Reactor Containment Area Level 7	Elevation	24.0 M
Direction	East-West	Damping	2, 3, 4, 5, 7, 10%

< SMART100 SSI 해석 >

i-SMR 운전층



Node	ENVELOPED	Spectra No.	GL+13_7m-EW
Direction	E-W	Elevation	13.7m
		Location	RPB WALL

< i-SMR SSI해석 >

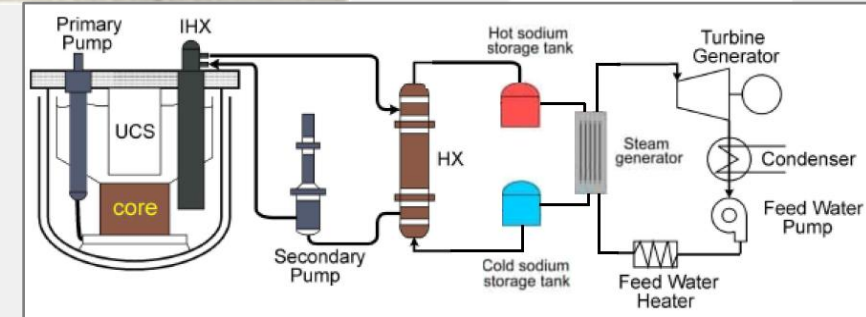
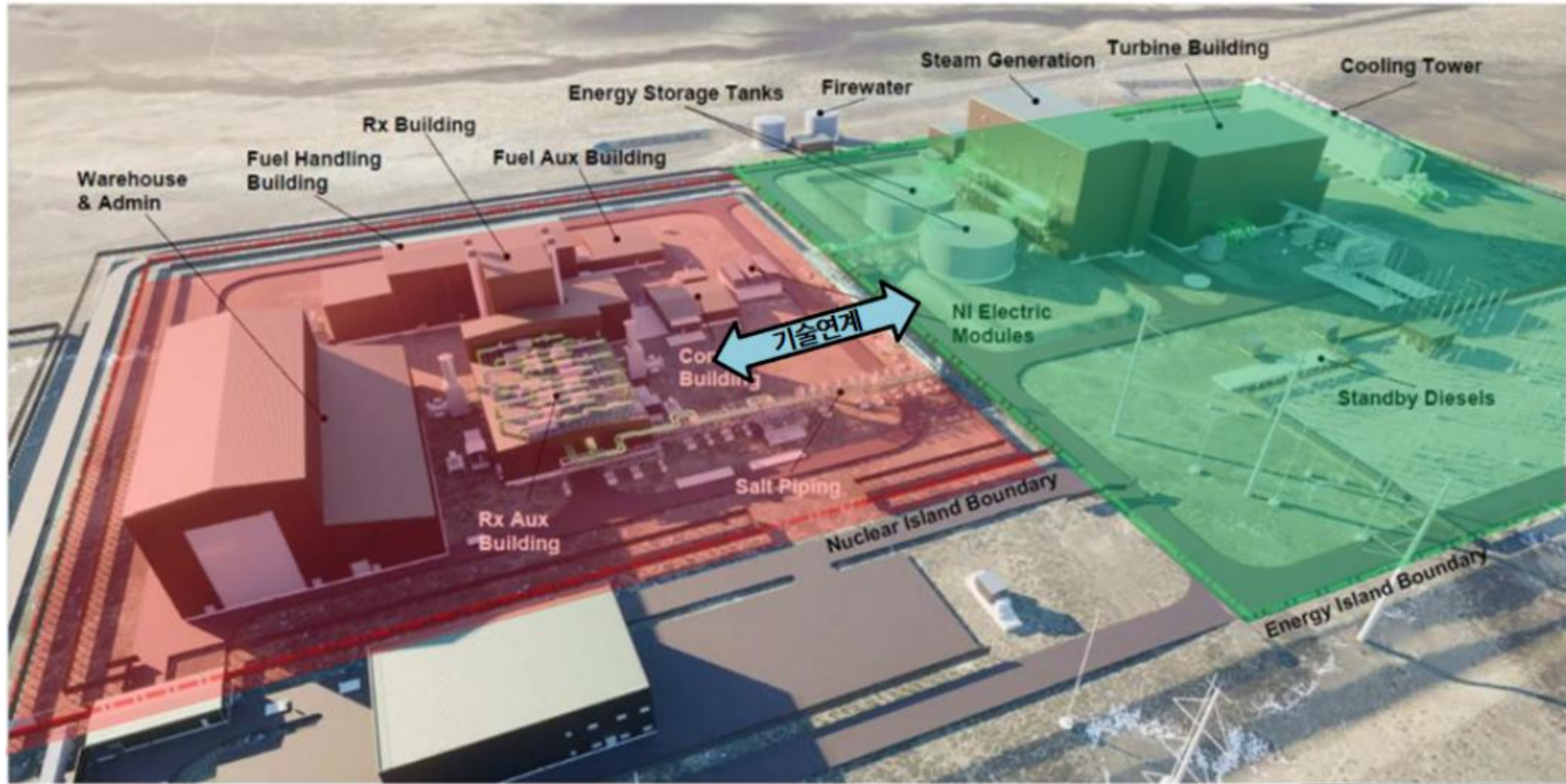
◆ 결론

- 혁신형 SMR SSAR 3.7장은 기존 SMART100 대비 두드러진 격차없이 제출할 예정. 내진설계에서 주요 변수는 국내 인허가 요건 및 기존 규제현안 사례를 반영하여 적용
 - 입력운동의 다중 시계열 세트 생성, 연약지반과 암반을 포함하는 포괄부지 적용, 콘크리트의 잠재적 균열, 측벽분리에 의한 접촉 상실, 입력운동의 경사 등 **확률론적 변동성과 다양성을 고려함.**
 - 강판콘크리트 구조의 감쇠비 별도 적용 (KEPIC SNG)
 - 혁신형 SMR 구조물의 깊은 매립(GL-22m)으로 인해서 해석틀의 한계가 발생. SSI 해석법을 기존 **부구조법에서 직접법으로 전환** 하고, 해석프로그램도 ACS SASSI에서 KIESSI-3D으로 변경
- 내진범주 I급 구조물(원자로보호건물, 제어건물)의 지진응답(SRS)을 SSAR에 반영하여 제출 예정
- KIESSI-3D 프로그램 소프트웨어품질보증(SQA) 절차 수행중
- 비내진범주 I급 구조물과 내진범주 I급 구조물의 상호작용* 영향 평가중
 - * 구조물-지반-구조물 상호작용 (SSSI)

PART II

장주기 SFR 면진설계 현황

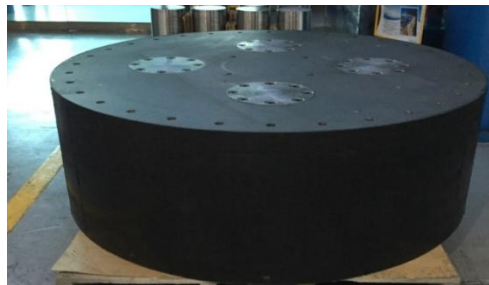
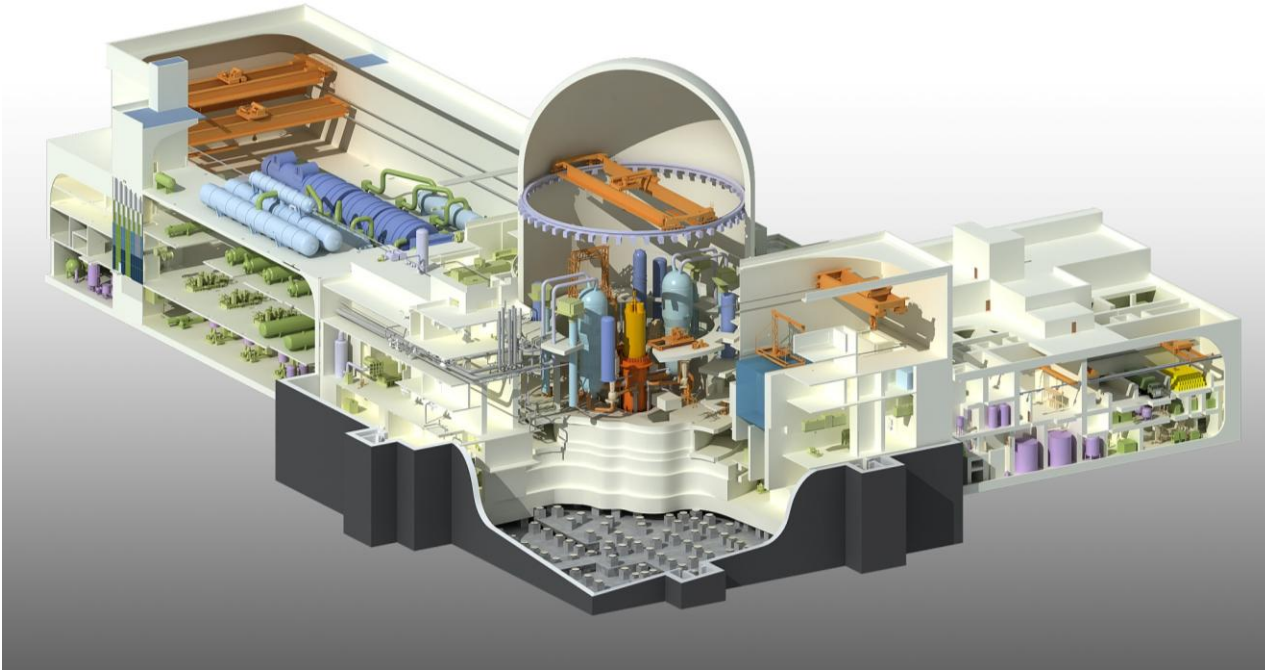
- 부지배치 및 최우선 요건
- 원전시설물 면진설계 사례



구분	H-SFR	PGSFR
원자로 유형	· 발전용 SFR	소각용 SFR
연료 종류	· 고농축 우라늄 (HALEU)	
핵연료 교체주기	· 장주기 20년	18개월
출력	· 200 MWe (예정) - 열저장설비로 최대 출력 300 MWe 가능	150 MWe
설계수명	· 60년	좌동
가동율	· 90%이상	75 %이상
설계 단순화	· 피동안전계통과 기능적 원자로건물로 설계 단순화	
	· 능동 안전계통과 관련 지원계통을 제거 (예정)	피동+능동
	· Functional Containment 설계 (예정)	일반Containment
안전성 목표	· 노심손상빈도(CDF) $\leq 1.0E-9/R\bar{Y}$ (예정)	1.0E-6/R \bar{Y}
	· 방사선 비상계획구역(EPZ) \leq 부지 경계 (예정)	
	· 풀형 원자로로 대형 냉각재상실사고 배제 · 피동안전계통 설계로 사고시 자연순환과 소듐 열특성을 활용하여 원자로 냉각 유지	좌동 피동안전계통
경제성 목표	· 내진 및 면진설계 , SSE 0.3g	좌동
	· 항공기충돌사고 고려한 설계	
	건설 단가 \leq (later) \$/kWe, 발전 단가 \leq (later) \$/MWh	
경제성 목표	· 설계 단순화로 SSC 대폭 감소	좌동
	· 장주기 운전(20년), 건설공기 단축, 가동율 90%이상 경제성 향상	
	· 운전 및 운영 인력 최소화	



➤ Seismic Isolated APR1400 (2011~2016)



kepik 전력산업기술기준
Korea Electric Power Industry Code

ST 구조총칙
General Structural Provisions

STC 면진시스템
Seismic Isolation System

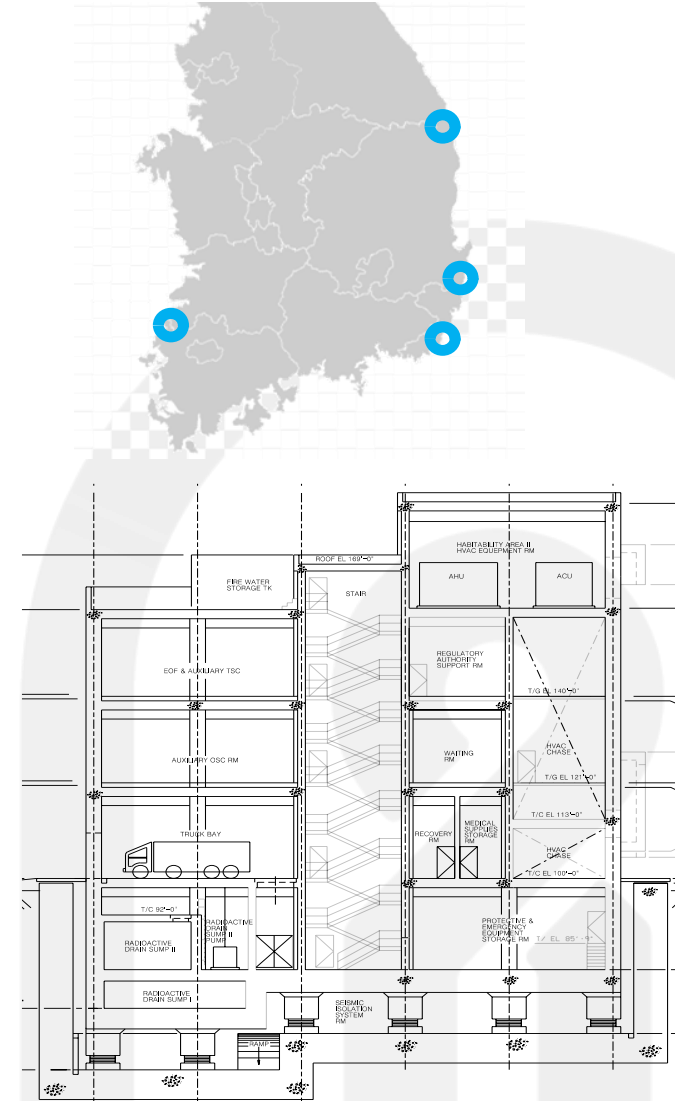
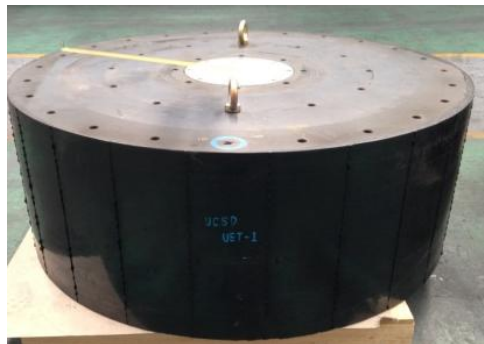
2017년 추록

KEPIC 정책위원회
구조전문위원회

Board of KEPIC
Structural T/C

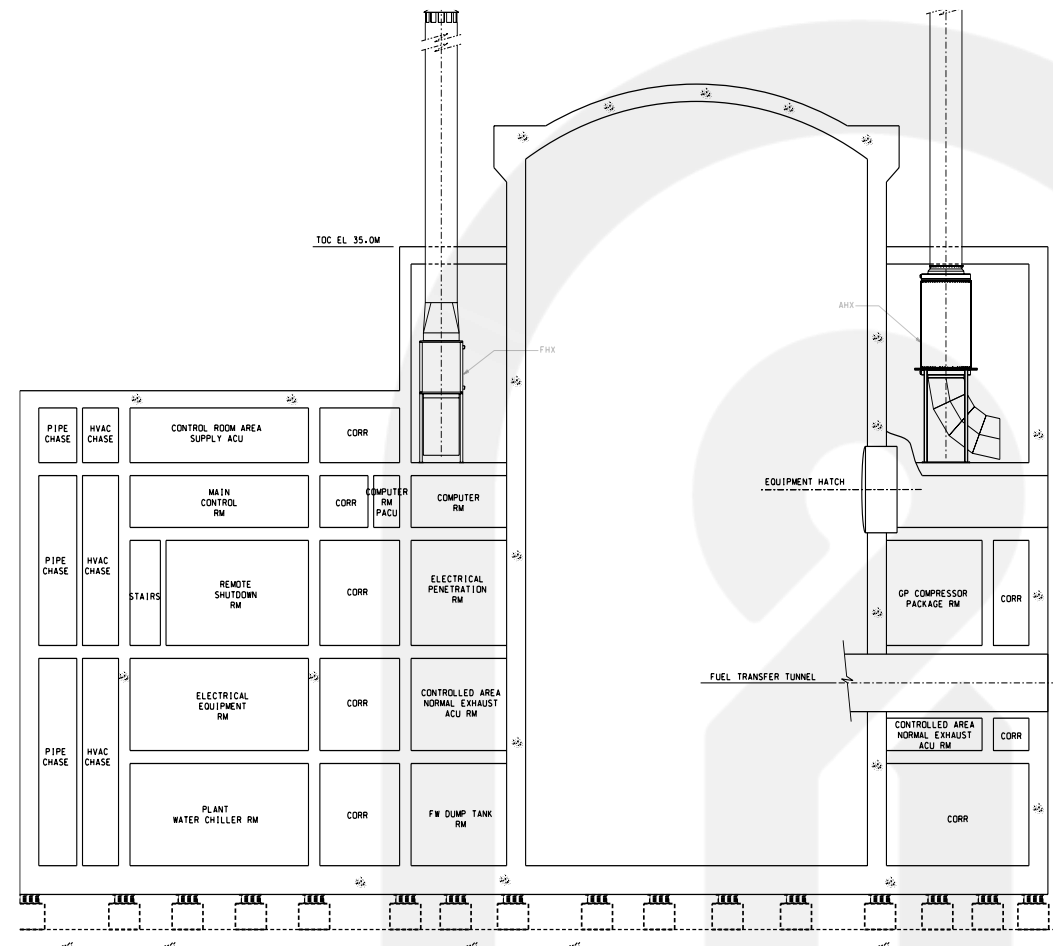
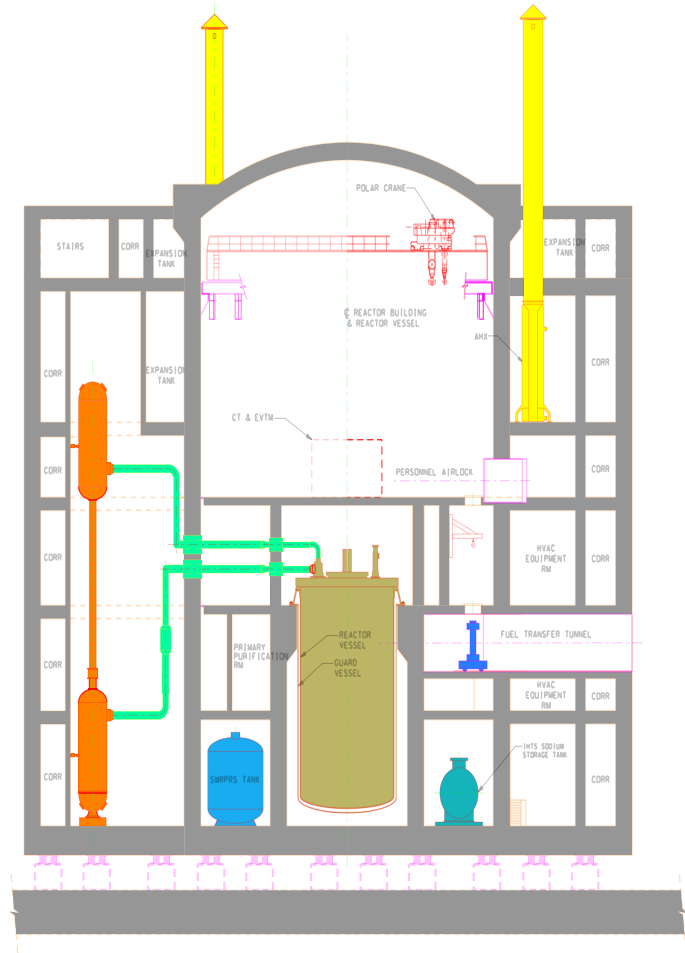
KEA 대한전기협회
KOREA ELECTRIC ASSOCIATION

➤ Emergency Response Base Building at 5-NPP sites (2020 ~)



➤ PGSFR (2016 ~ 2022)

- Fuel Waste Reactor
- Seismic Isolated Reinforced Concrete Structure

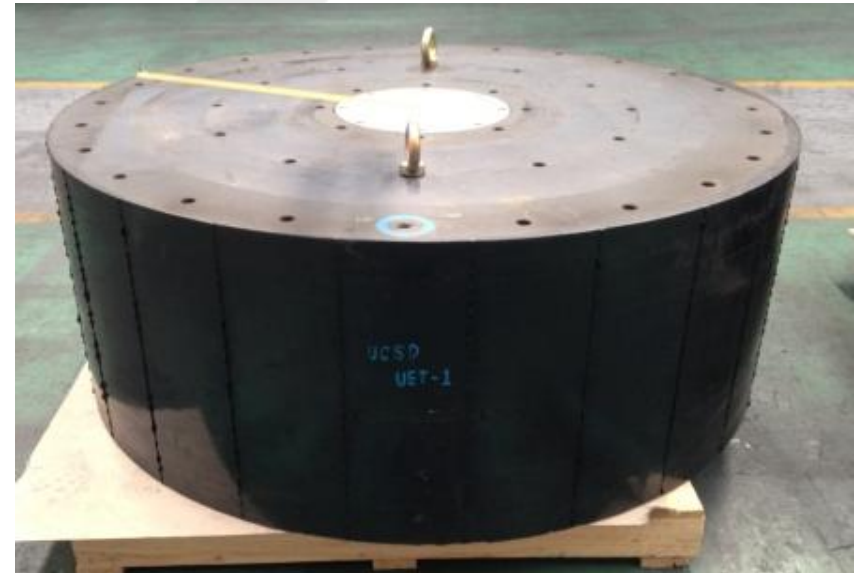
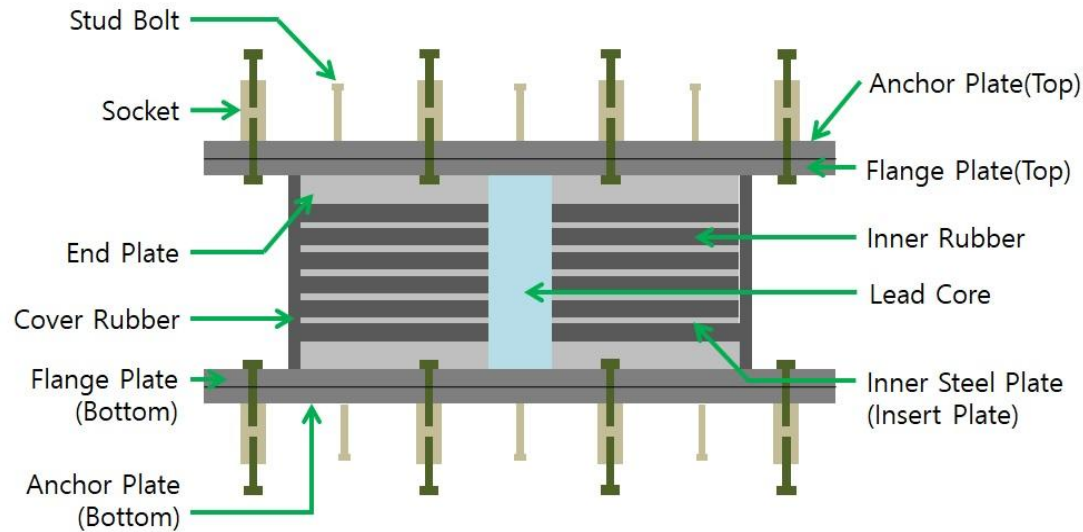


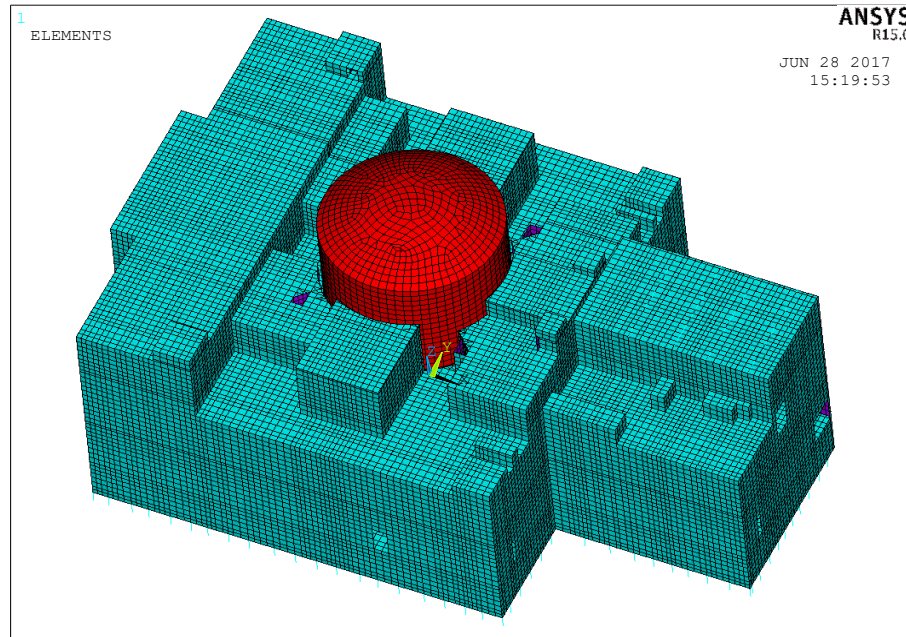
➤ Background

- Seismic Demand: **SSE 0.3g**, OBE 0.1g
- Nuclear containment shell & NSSS should be maintained against seismic loads **greater than 0.2g**

➤ Bearing type

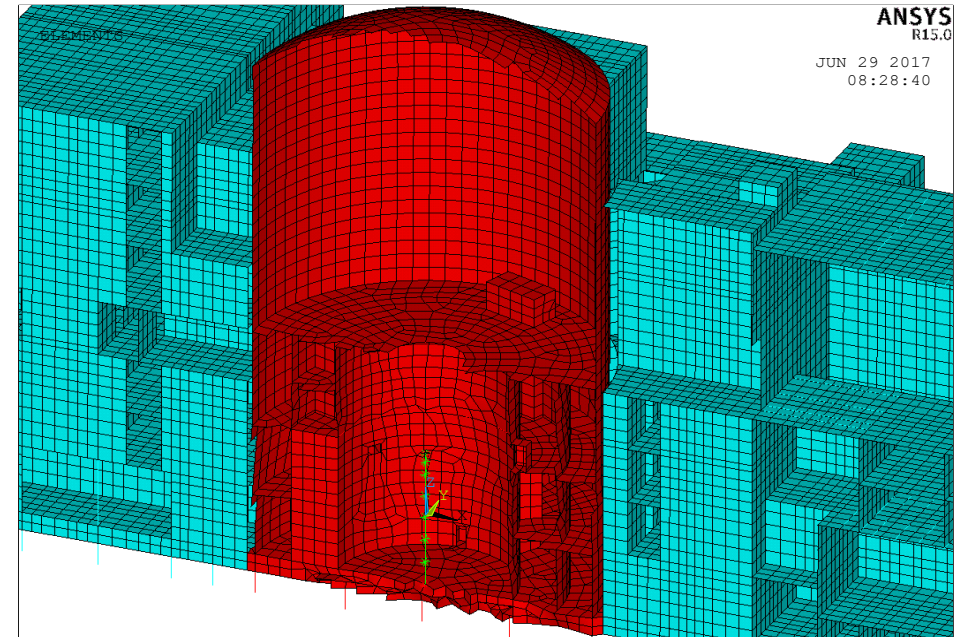
- **LRB (Lead Rubber Bearing) – 300ea**





➤ Structural Information

- Total Weight : 300,500 tonf
- Maximum Dimension : 121m × 81m × 74m (B×D×H)
- **NI : RCB + AB + FB**
- Base Isolation System

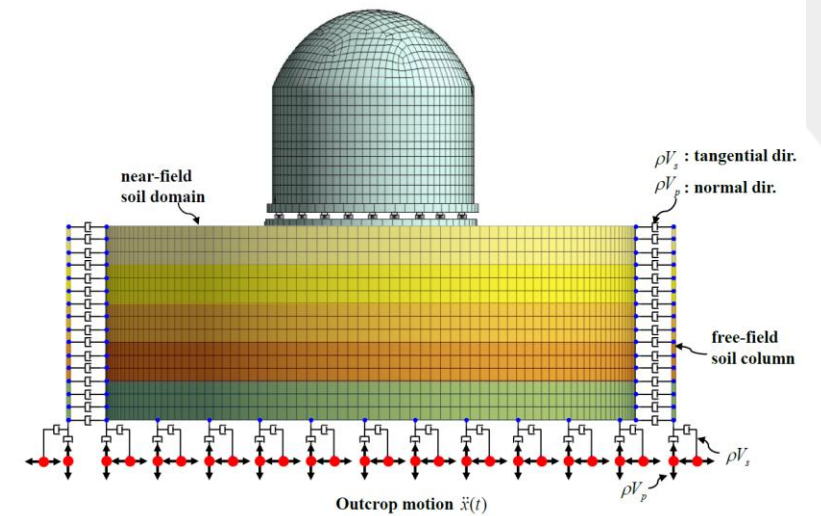
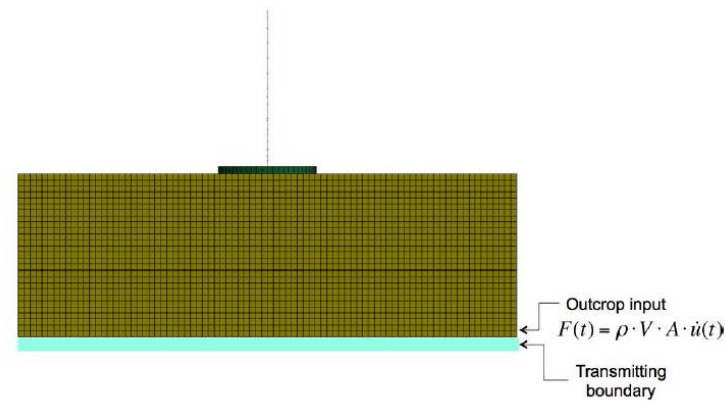
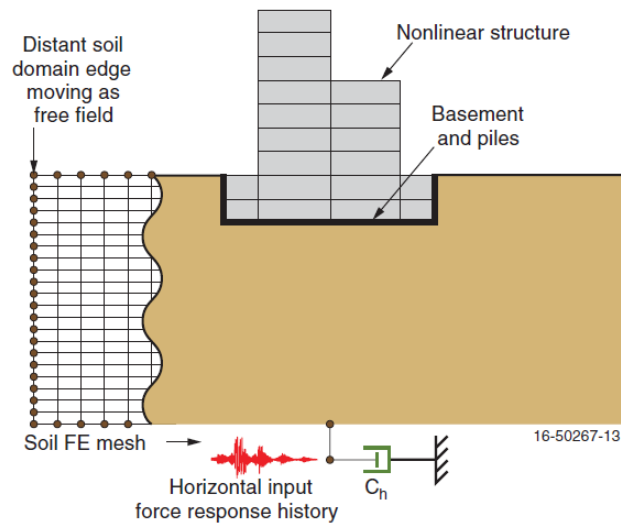


➤ Model Information

- Used Program : ANSYS APDL 15.07
- Total Number of Nodes : 102,026
- Total Number of Elements : 197,025
- Used Elements : Solid185 & Shell181
- Non-linear Link : Combin40

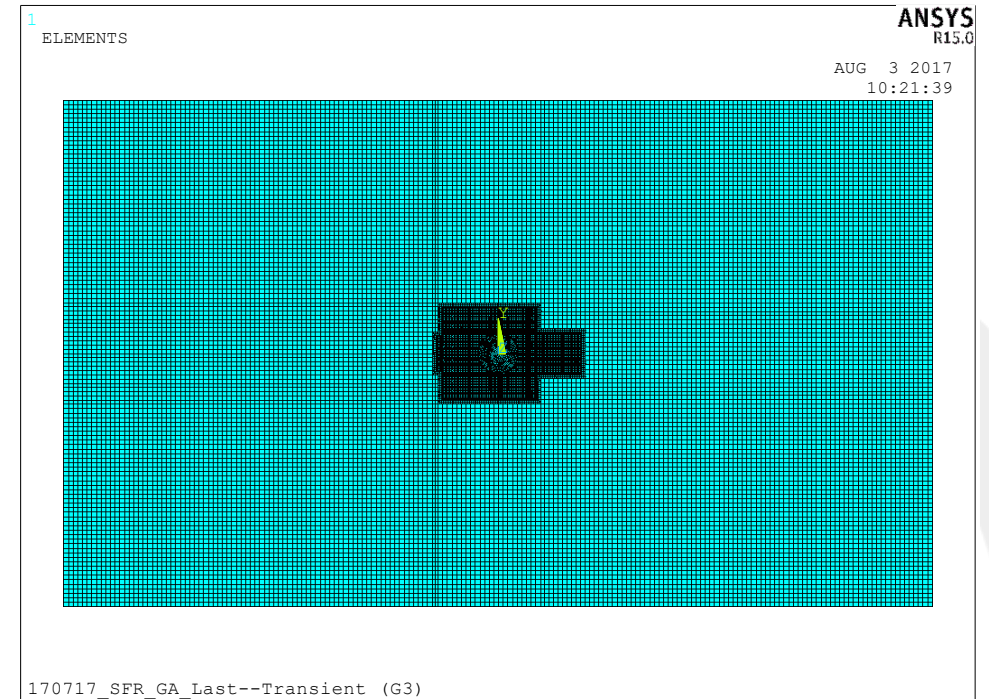
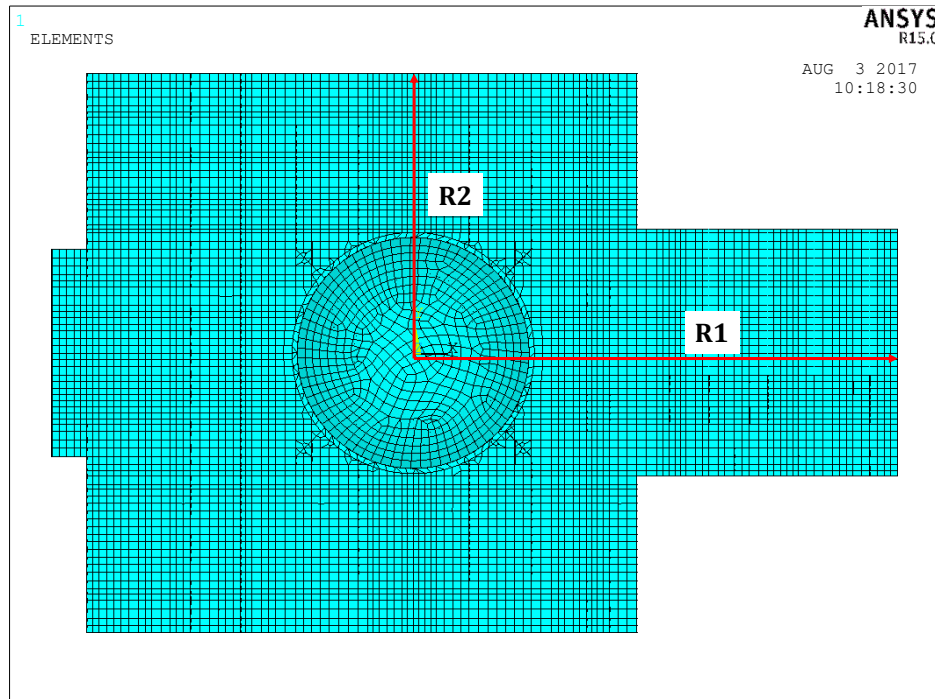
➤ Direct Method (DM) using Conventional Package

- Need to model both Soil and Structure
- Used Finite Element Model & Implicit Direct Integral Method
- Define Absorbing Boundary & Soil Column Element for Far Field



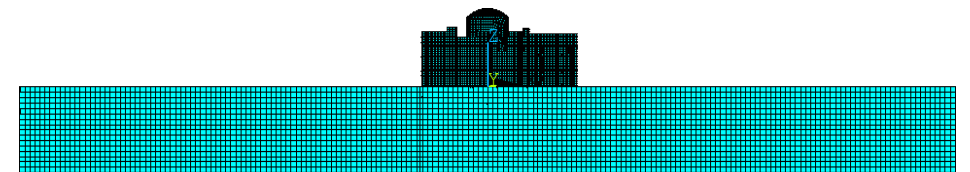
- Control point : Bottom of Soil

- Artificial Absorbing Boundary : Viscous Damper between Bedrock and Outcrop

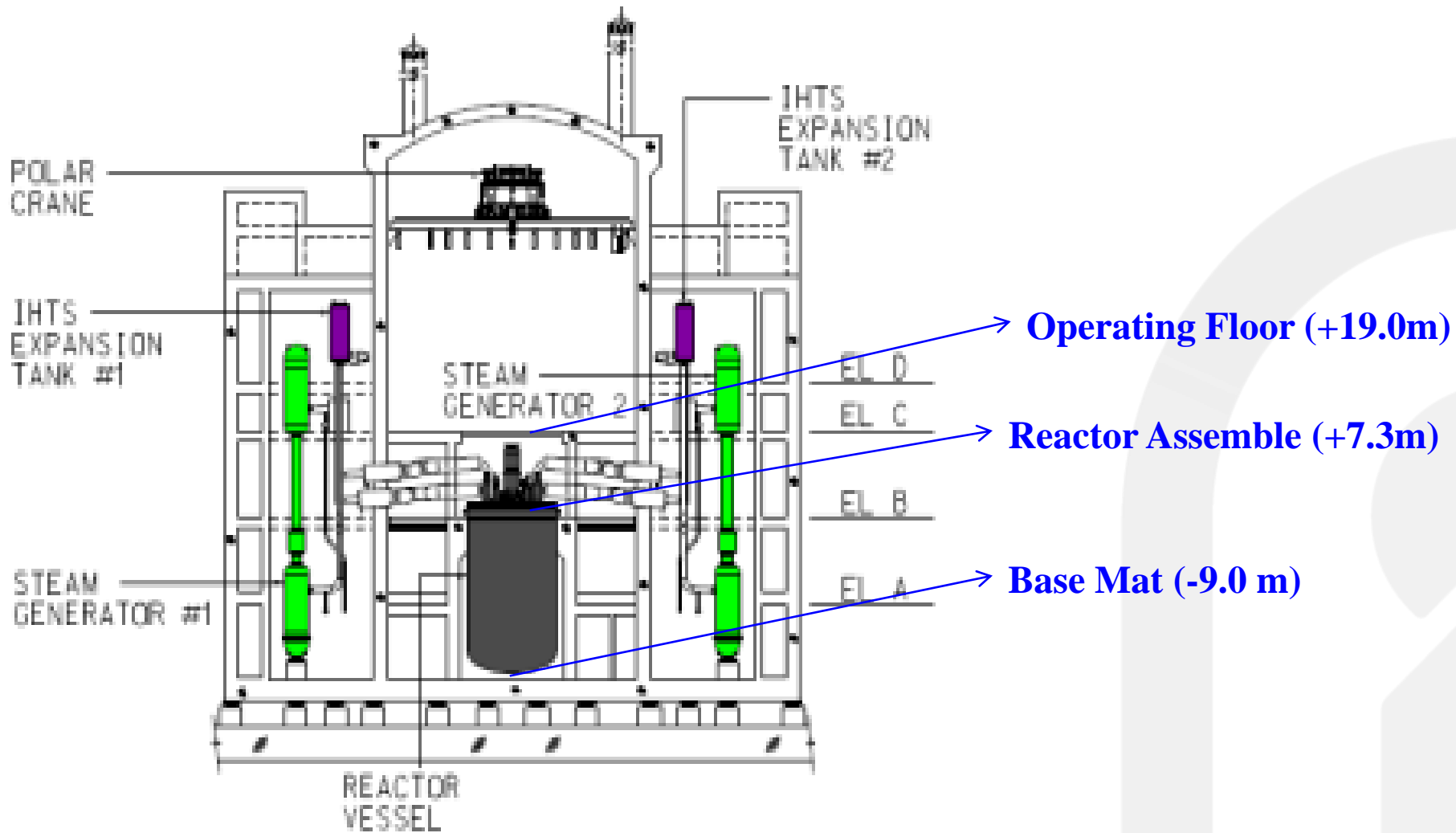


➤ SSI Model Information

- Structure located on Ground Surface
- Total Number of Nodes : 330,000
- Total Number of Elements : 400,000
- Shear Wave Velocity : 2400 m/s (8000 ft/s, Hard Rock Site)
- Real Site Profile : NOT defined



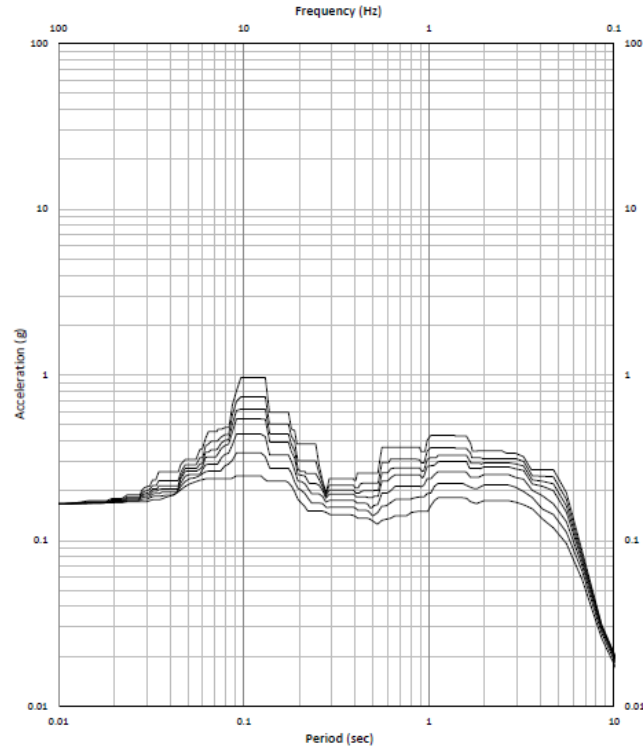
➤ Interested Points



➤ Widened Floor Response Spectra (2%, 3%, 4%, 5%, 7%, 10% and 15%)

FLOOR RESPONSE SPECTRA OF PGSFR
BASE ISOLATED PGSFR

PROJECT : TRG08
SAFETY-RELATED
DAMPING : 2% 3% 4% 5% 7% 10% 15%

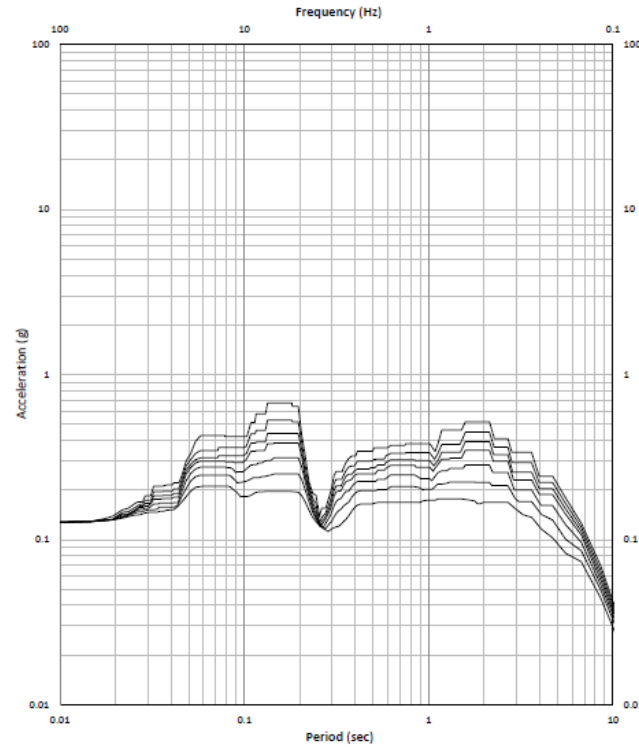


Node 129519
Direction E-W
Spectra No. SWRPRS SDT#1-X
Elevation -11.15m
Location NSSS -11.1

EW-Dir.

FLOOR RESPONSE SPECTRA OF PGSFR
BASE ISOLATED PGSFR

PROJECT : TRG08
SAFETY-RELATED
DAMPING : 2% 3% 4% 5% 7% 10% 15%

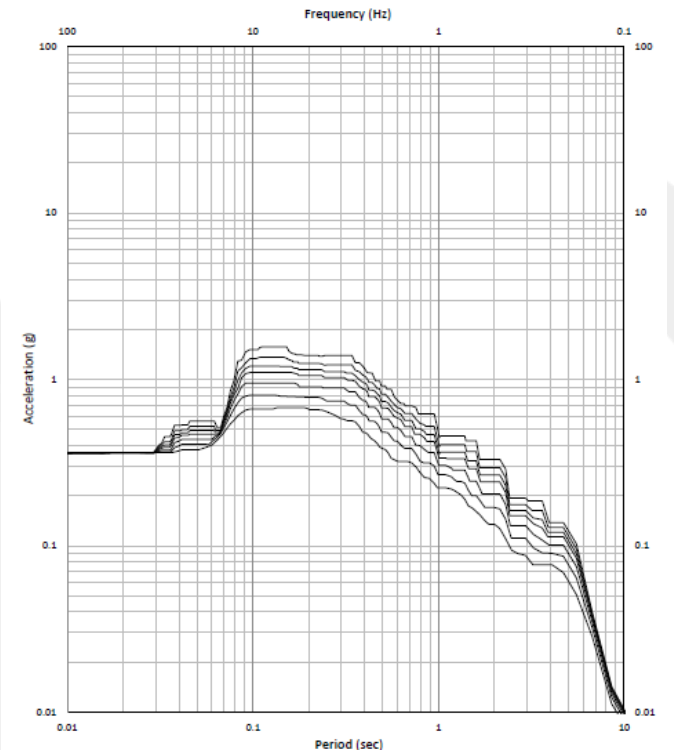


Node 129519
Direction N-S
Spectra No. SWRPRS SDT#1-Y
Elevation -11.15m
Location NSSS -11.1

NS-Dir.

FLOOR RESPONSE SPECTRA OF PGSFR
BASE ISOLATED PGSFR

PROJECT : TRG08
SAFETY-RELATED
DAMPING : 2% 3% 4% 5% 7% 10% 15%



Node 129519
Direction V-T
Spectra No. SWRPRS SDT#1-Z
Elevation -11.15m
Location NSSS -11.1

VT-Dir.

PART IV

Q&A

감사합니다