EXPERT REPORT - 2

Client: **Public Investment Management Office**
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Research framework: Expert design of base isolation system of BIOSENSE Lab Building Modul against seismic and external vibrations and formulation of experimental testing program of its operational state

Project title: Formulation of testing program of operational state of base isolated BIOSENSE Lab Building Modul

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Content

1. Introductory remarks

The building structure of the laboratory has to meet much higher requirements than conventional buildings. The building must remain harmless in the event of an earthquake to prevent any damage to the expensive laboratory equipment. This requirement under seismic loading and operational loading shall be achieved for the BIOSENSE laboratory by means of a base isolation system complemented by well-designed damping devices. Therefore, for the design of base isolation of BIOSENSE Lab Building Modul against earthquake effects and external vibrations, technology described in details in Expert report – 1 is applied.

In order to complete realisation of building module isolation it is needed to investigate basic dynamic and operational characteristics of the structure and its parts. In the practice, several specific experimental methods (see Appendix-A) developed for this purpose are used. Based on the experience and recommendations of the best practice, adequate program for testing of operational state of base isolated BIOSENSE Lab Building Modul is given in this report. The purpose of this testing program is to collect the data for adequate design of base isolation and damper devices, as well as global system identification of the BIOSENSE Lab Building Modul after installation of devices and completion of the structure.

Recommended testing procedures and program should be realised with the constant supervision of design and expert team.

2. Short description of proposed testing program

Brief description of four methods that can be applied for testing of base isolated BIOSENSE Lab Building Modul is given in Appendix-A. Each of the methods requires a use of special and sensitive equipment with the detailed and well-prepared testing program. The smooth and high-precise operation of the highly sensitive equipment must be ensured by additional measures for the specific site conditions. Therefore, it is necessary to carry out measurements at the building site prior to construction in order to record and analyse the vibrational effects of traffic and other external sources. Furthermore, internal sources like walking, in-lab traffic, building services and other lab equipment can generate higher vibration levels than external sources and need to be identified in advance in order to derive an appropriate structural design of all building components.

The described external and internal vibration sources need to be controlled to meet the criteria for functioning equipment. As manufacturer's criteria for equipment are often not available, it is required to take well-accepted generic vibration criteria curves (VC) that were developed over the last 20 years and implemented in international and European guidelines into account. In order to meet the vibration criteria adequate measures shall be developed and described (e.g. increased floor stiffness, isolation, slab spans…)

After completion of the BIOSENSE laboratory construction, the functionality of the building under operational conditions shall be checked and documented by means of measurements at site. The measurements shall include a detailed dynamic system identification and investigation of the overall vibrational structural behaviour of the isolated building module and local measurements of slab vibrations at locations with highly sensitive equipment.

The assessment of the dynamic properties of the base isolated structure with damping devices structure shall comprise studies and measurements before construction, measurements after completion of the laboratory building and continuous monitoring as detailed described in the following table.

All measurements shall be executed based on the principles for carrying out vibration measurement and processing data with regard to evaluating vibration effects according to

ISO 4866. ISO 18431-1 shall be taken into account for the analysis of vibration, ISO 18431-2 for definition of time-domain windows and ISO 18341-3 for time frequency analysis. The methods of measurement, algorithms for analysis and the report of vibration data for sensitive equipment in buildings shall be applied according to ISO/TS 10811-1, and the methods for the classification of vibration measurements shall be classified in accordance with ISO/TS 10811-2. If required, VC curves provided as recommended best practise by the Institute of Environmental Sciences and Technology shall be applied (e.g. IEST-RP-CC012 for cleanroom design). Furthermore, the recommendations in ISO 10137 on the evaluation of serviceability against vibrations of buildings, and walkways within buildings or connecting them or outside of buildings shall be considered.

3. Execution steps and estimation of costs for the proposed testing program

Based on the task and purpose of the testing program using all the available knowledge and experience in this field, steps and estimation of costs for the execution of testing program of operational state of base isolated BIOSENSE Lab Building Modul are given as follows:

Pos.	Specification	Price
1	Measurements of external vibrations at the building site prior to construction in order to record and analyse the vibrational effects of traffic and other external sources. The measurement period must be carried out in such a way that the vibrations can be regarded as representative for the building location.	
2	Identification and specification of internal vibration sources like walking, in-lab traffic, building services, generators and other lab equipment. The study requires close cooperation with the project planning and the end users.	
3	Collection and compilation of thresholds and limit curves for the planned technical equipment in consultation with the end users and the manufacturers of vibration-sensitive equipment. If criteria for specific equipment are not available, well-accepted generic vibration criteria curves (VC) shall be chosen and applied. For each building floor level the requirements shall be evaluated and summarized.	
4	Analysis and evaluation of external vibrations (Pos. 1) and internal vibration sources (Pos. 2). Simulation of vibrations use for sensitive technical equipment and comparison with the thresholds and limit curves obtained in Pos. 3. Development of required measures (e.g. slab stiffening, isolation, damping devices, ...) based on the simulation results.	
5	Dynamic measurements and global system identification of the BIOSENSE building under ambient vibration and different operational conditions. Execution of operational modal analysis based on the dynamic measurements with identification of eigenfrequencies and eigenmodes. The type, number and position of sensors[1] shall be chosen according to the required sensitivity and accuracy.	

6	Dynamic measurements and global system identification of the BIOSENSE building under horizontal force-based vibration generated with a dynamic shaker system[2] with gradually increase of force and frequency to identify the resonant behaviour. The force-based vibration will be applied in both building directions. Execution of operational modal analysis based on the dynamic measurements with identification of eigenfrequencies and eigenmodes. The type, number and position of sensors[1] shall be chosen according to the required sensitivity and accuracy.	
7	Dynamic measurements of the slabs on each floor level with vertical force-based vibration using a dynamic shaker system[2] with gradually increase of force and frequency to identify the resonant behaviour. Identification of eigenfrequencies, corresponding eigenmodes and amplitudes. The type, number and position of sensors[1] shall be chosen according to the required sensitivity and accuracy.	
8	Dynamic measurements of the slabs on each floor level under operational conditions. Identification of eigenfrequencies and corresponding eigenmodes and vibrations amplitudes. The type, number and position of sensors[1] shall be chosen according to the required sensitivity and accuracy.	
9	Installation of a permanent monitoring with determination of dynamic loading levels during future seismic events. The monitoring system shall include one acceleration sensor on each building level, whereas the power supply and network connection are provided by the building owner. The measurement data shall be transferred and saved on a hardware system provided by the building owner. The evaluation of the measurement data shall include frequency analysis and check of thresholds for the accelerations by means of a simple evaluation tool.	

[1] The correct functioning of all applied sensors must be verified by calibration protocols according to ISO 16063 or equivalent calibration protocols prepared by a third party not older than three years.

[2] The correct functioning of the applied shaker system must be verified by calibration protocols prepared by a third party not older than three years.

4. Appendix-A: Brief description of the available methods for testing of operational state of base isolated BIOSENSE lab Building modul

TABLE OF CONTENTS

1. AMBIENT VIBRATION TEST METHOD		
1.1	GENERAL The ambient vibration testing procedure consists of real time recording of the vibrations and processing of the records. This method of structural testing is based on measuring the small structural vibrations caused by the ambient forces. Ambient forces may be caused by the wind, the traffic noise or some other micro-tremor. An advantage of the ambient vibration over the forced vibration surveys is that usually light equipments are required. Further it requires only relatively short and simple field measurements, and the measuring instruments can be installed and operated by a smaller number of operators . The method is very fast and relatively simple procedure and can be performed on a structure in use without disturbing its normal functioning. Since the amplitudes of structural vibrations are small, the ambient vibration tests describe the linear behavior of the structures. However, earlier studies found that testing based on ambient vibrations gives essentially the same results as would be obtained from the forced vibration experiments, in the linear range of excitation. One of the most frequent uses of the method involves identification of dynamic characteristics of various full scale structures. Some of the other applications of Ambient vibration testing are calibration of analytical models of structures; structural health monitoring; to identify and to monitor changes of natural frequencies of damaged, and repaired structures; to predict difference in response due to different soil conditions and type of excitation etc. The ambient vibration tests are “complete” full-scale experiments. Even wisely devised laboratory experiments will characterize only those aspects of the problem that the experiment designer had selected to study and integrated into the model. The best and most complete laboratory tests can validate and quantify only those aspects of the problem that the investigators know. Except when fortunate accidents occur, we do not know how to model what we are not aware of and what we do not understand. The full-scale ambient vibration tests give	*Advanced assessment of real structural conditions of base isolated building module*

	away an entirely different situation that cannot be commanded effortlessly. The as-built environment holds all the belongings of reality. We only have to find nifty ways to discover record and interpret this reality.	
1.2	INSTRUMENTATION As described, the ambient vibration testing (AVT) process involves sensing the structural vibrations caused by ambient forces, recording the vibration responses and then analyzing the data to arrive at dynamic characteristics of the structure. Thus the instrumentation for AVT may be categorized into three main units: (1) Data Acquisition System; (2) Power System and (3) Sensing System.	
1.2.1	Data Acquisition System Data acquisition is a procedure in which the analog data from the sensing device is converted into digital data and stored permanently. The data need to be checked for errors related to the quantization, aliasing, filtering and leakage and need to be processed for error mitigation and parameter estimation. Parameter estimation involves identification of the magnitude and phase of different signals obtained. For this purpose data logger and computer are used. A data logger is electronic device which changes an analog input into a digital time series representation. At the time of setting up and programming a data logger, following precautions should be taken: (1) Set up in safe place free from moisture; (2) Supplied with consistent and adequate power; (3) Programmed with the right recording parameters; (4) Allied properly to the sensor for receiving accurate timing (from GPS); (5) Recording data on site to non-volatile memory. In practice there are three types of data logger namely (i) 1-channel data logger, (ii) 3-channel data logger and (iii) Multi-channel data logger.	
1.2.2	Power System In case of non-availability of electronic power, the most common power source is a battery. Batteries are of two	

	main types: primary and secondary. Primary batteries are used once then discarded and secondary batteries are rechargeable. Mostly deep cycle lead-acid batteries are used to specific data acquisition system. The capacity and size of the lead-acid battery will depend on the type of data logger, type of sensor, size of solar panel, telemetry and geographic location. Now a days, a system which is a combination of enclosure, solar charge controller and connectors is being used frequently which ensure that batteries are charged and data loggers and sensors are received power simultaneously. It has power output, solar panel input and battery input. This system is specifically named as power system having load capacity of 12-15 amp and a low voltage disconnect (LVD) to safeguard battery from damage and operated with nominal 12 volt solar panel and deep cycle gel-cell lead acid battery. The power box should have features like water resistance, smaller size, maximum power point tracking, lower self-consumption and regulated and unregulated output.	
1.2.3	Sensing System The sensing system is targeted to measure the structural responses and the equipment that actually detects and quantifies motion is called sensor. Sensors send this information to the data logger through cable. Details of different sensors used for measurement have been provided in related literature. Sensors have been developed for measurement of different parameters such as strain, temperature, pressure, wind speed, velocity, displacement, and acceleration, etc. and depending upon the desired parameters work on different operating principle. Sensors which are commonly used in AVT are Forced Balanced Accelerometers (FBA) and Ranger Seismometers. Acceleration is a common parameter for short and long term monitoring of prototype structures and model testing purposes. Many types of accelerometers are available, such as capacitive accelerometers, piezoelectric accelerometers, strain gauge accelerometers, fiber grating accelerometers, micro-electro-mechanical systems (MEMS) accelerometers and servo accelerometers. At a specific	

	point of the structure, accelerometer measures accelerations and typically generates electric signals in the form of voltage which is read by a data acquisition system. If signals are weak, conditioning amplifiers are used to amplify the signals. Different types of sensors are described below: Broadband sensors are 3-component seismometers competent of sensing ground waves having frequency in the range of .01 Hz to 10 Hz. These sensors are very frequently exercised in passive experiments and regional earthquake. With enough signal, however, 120 sec. and 240 sec. velocity transducers can resolve signals with periods much longer than the corners period. Corner period is defined as the period at which magnification drops by 3db of peak value. Intermediate sensors are three component seismometers with corner periods in the 30 to 40 seconds range. These sensors are capable of sensing ground motions of much longer periods than their corner periods, if the long-period amplitudes are sufficient. Short-periods sensors are three component seismometers that cover higher frequency bands usually 1Hz to 100+Hz. These sensors are used in both passive and active source experiments. They have a flat response to ground velocity for frequencies greater than this corner frequency. High-Frequency Sensors are very rugged seismometers that cover even higher frequency bands of range 4.5 Hz to 100+ Hz. These sensors are most-often used in active-source experiments and often referred to as geophones. Accelerometers also known as strong motion sensors are devised to assess the large amplitude, high frequency seismic waves typical of large local earthquakes, and operate in the frequency band 0 Hz to 100+ Hz.	
1.3 **1.3.1**	PROCESSING OF TESTING DATA ARTeMIS Modal ARTeMIS Modal is a powerful and versatile tool for Operational Modal Analysis. Its ability to produce validated modal parameter estimates, based on parallel analysis of up to eight different analysis techniques, makes it the natural choice in mission critical applications.	

	From the patented Frequency Domain Decomposition (FDD) techniques to the unique Crystal Clear Stochastic Subspace Identification (SSI) techniques, ARTeMIS Modal enable engineers to obtain validated estimates the mode shapes, natural frequencies and damping ratios, directly from the raw measured time series data of structures under natural conditions. The software is designed for the vast number of cases where it is preferred not to control or measure the loading. The software is used by engineers all over the world for modal analysis of all kinds of structures: • Operating machinery or other mechanical structures with or without rotating components. • Large civil engineering structures like bridges, dams and buildings subjected to ambient loads. • Structures with rotating components such as wind turbines, stream turbines, engines and gas compressors. • Maritime structures like ships and offshore structures. • Automotive, trucks, trains and vehicles and sub parts systems. • Aerospace structures such as launch vehicles and aircrafts. • The software is an open, and user friendly platform for modal testing, modal analysis and modal problem solving. If we can measure the vibrations, ARTeMIS Modal can give you the modes in terms of mode shape, natural frequency and damping ratio.	
1.3.2	Major Benefits • In-situ testing of a structure – True boundaries. • Natural environment – True excitation forces even in the presence of deterministic signals (harmonics). • Test during normal service state – No interruption needed - increased productivity. • Use operational forces - No artificial excitation needed. • Modal parameter results describes the true service state of the structure. • Can be used on extremely small or large structures – size does not matter.	

	• Scalable software – Unlimited amount of sensors and data points. • Handles multiple test setups (rowing sensors) and multiple reference points for increased mode shape accuracy. • Fast and automatic results – Saves time. • User friendly – Have your first modal parameters estimated in a matter of minutes. • Versatile – If you can measure the vibration – ARTeMIS will always give you the answer. • Open - Major data input file formats supported. • Outstanding results – Validated output based on several parallel modal analysis – Accuracy. Results can directly be used by e.g. FE updating software solutions.	
1.4	TESTING OF BIOSENSE ISOLATED BUILDING MODULE These building structures are generally treated as equivalent discrete multi-degree of freedom system. At the floor level, the various masses of the floor system together with half the supporting systems (columns and walls) located both above and below the floor level are assumed to be concentrated. With increase in number of storey, the fundamental period of the structure increases. Multi-storey buildings are usually tested for safety due to wind forces but some regions of a building would be more critical for earthquake forces as compared to wind and vice versa. Hence, there is a need to check the design parameters for both types of forces. Ambient Vibration testing is a good tool to find the dynamic parameters of multi-storey building experimentally without disturbing the normal functioning of the building.	

2 FORCED VIBRATION TEST METHOD		
2.1	ADVANCES OF FORCED VIBRATION TEST METHOD A great deal of knowledge about the performance of structural systems, such as bridges, can be created using full-scale, in-situ experimentation on existing structures. Full-scale testing offers several advantages as it is free from many assumptions and simplifications inherently present in laboratory experiments and numerical simulations. For example, soil-structure interaction, non-structural components, and nonlinearities in stiffness and energy dissipation are always present in their true form in full-scale, in-situ testing. Thus, full-scale experimentation results present the ground truth about structural performance and indeed provide the ultimate test for both actual constructed systems and laboratory and numerical investigations. The performance evaluated this way can be used for advanced assessment of structural condition, detection of damage, aging and deterioration, evaluation of the construction quality, validation of design assumptions, and also as lessons for future design and construction of similar structures.	*Advanced assessment of real structural conditions of base isolated building module*
2.2	FORCED VIBRATION TEST The forced vibration testing methodology is based on resonant concept. By the application of a dynamic harmonic force on the top of the building, it is possible to excite the resonant frequencies of the building, if the frequency of the force is equal to one of the natural frequencies of the building. The frequency of the force can be gradually changed in small steps within the range of 0.5-16.0 Hz. The resonant state is reached when the acceleration response at the measurement point become maximum and then decrease even the frequency of the force still increase. On this manner, frequency response curves can be obtained for each orthogonal direction and torsion. The forced vibration equipment, shown in Figure 5, consists of an eccentric mass shaker for excitation with a harmonic sinusoidal force within the frequency range 1-15 Hz as well as signal recording equipment: data acquisition	

	system 16 channels - National Instruments-USA, Kistler accelerometers 5g, and signal amplifier- Kistler-USA, for accelerometers (8 channels), signal amplifier-Kyowa, for Kyowa strain-gauges KFC-5 (8 channels). A labtop computer can be used to process the digitized data.	

3 FORCED QUASI-STATIC CYCLIC TESTS OF BASE ISOLATED SYSTEM		
3.1	LOADING OF ISOLATION SYSTEM In order to carry out the stated specific forced quasi-static cyclic test of the implemented base isolated system, required is the design and construction of special loading system by which a horizontal static force could be repeatedly applied. The force should be applied to the upper building segment, just above the isolation system. Special loading system should be designed and constructed according to the existing building geometry and available supporting conditions for the implemented hydraulic actuator. The final loading system, the testing scheme and location of the recording instruments should be defined in the previously elaborated full testing plan and testing procedure.	*Advanced assessment of real structural conditions of base isolated building module*
3.2	INSTRUMENTATION AND RECORDING SYSTEM During dynamic test it is required to record displacements and accelerations. Accordingly, to record displacements and accelerations it is usually needed to be applied LVDT sensors and accelerometers, respectively. During static test it is required to record displacements and forces by respective sensors.	
3.3	TESTING PROCEDURE Several independent cyclic tests can be performed. Each test can include cycles of loading and unloading under displacement control. Different static tests of the isolation system can be realized up to a maximum horizontal displacement of 20% of the design value. From the obtained data, non-linear behavior of the isolation system and stiffness degradation can be studied. It gives the basis to suppose that if would be possible to continue the tests and reach, for example, the design displacement, the degradation of stiffness from cycle to cycle would not be as big, as it was for the first two cycles.	

	EXAMPLE TEST: The average tangent stiffness at the third and fourth cycles of loading, which is equal to about 29 kN/mm, can be accepted with some assumption as the stiffness of the isolation system at the design displacement. If it is so, then the actual stiffness of one seismic isolator will be equal to 29:39=0.74 kN/mm, which is about 9% less than the design stiffness. Thus, the static tests allowed to reveal pretty good correspondence between design and real characteristics of the isolation system.	

4 PULL-OUT BASED FORCED VIBRATION TEST METHOD		
4.1	ADVANCES OF PULL-OUT VIBRATION TESTS A great deal of knowledge about the performance of structural systems, such as bridges, can be created using full-scale, in-situ experimentation on existing structures. Full-scale testing offers several advantages as it is free from many assumptions and simplifications inherently present in laboratory experiments and numerical simulations. For example, soil-structure interaction, non-structural components, and nonlinearities in stiffness and energy dissipation are always present in their true form in full-scale, in-situ testing. Thus, full-scale experimentation results present the ground truth about structural performance and indeed provide the ultimate test for both actual constructed systems and laboratory and numerical investigations. The performance evaluated this way can be used for advanced assessment of structural condition, detection of damage, aging and deterioration, evaluation of the construction quality, validation of design assumptions, and also as lessons for future design and construction of similar structures.	*Advanced assessment of real structural conditions of base isolated building module*
4.2	PULL-OUT VIBRATION TEST PROCEDURE The pull-out vibration test procedure represent specific type of forced vibration testing methodology. With initial pull-out deformation and its abrupt release it is possible to excite vibration of the building. We are able to record actual vibration characteristics of the building representing real state of damped vibration.	