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## Structural Identification: Opportunities and Challenges

--Manuscript Draft--

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<b>Corresponding Author:</b>	Ahmet Emin Aktan, Ph.D. Drexel University Philadelphia, PA UNITED STATES
<b>Corresponding Author E-Mail:</b>	aaktan@drexel.edu
<b>Order of Authors:</b>	Ahmet Emin Aktan, Ph.D. James Brownjohn

Editor, Journals

ASCE

Dear Editor:

Please find attached a Forum Paper we were invited, together with Dr. James Brownjohn, to write and submit to a special issue of the Journal of Structural Engineering dedicated to Structural identification. Together with Dr. Brownjohn we submitted a draft for review, revisions to which were advised by the Editors. These revisions were made and several additional comments were received. We are now submitting the paper after its second revision.

Structural identification is a very important concept that will potentially help the civil engineering profession to understand the actual mechanical characteristics of constructed systems, incorporating the interactions between site, soil, foundations and the superstructure as well as their intrinsic and transient actions. Proper applications would lead to knowledge about the ground truth of as-constructed operating civil engineering products as opposed to empirical estimates of properties, performance and behavior during design. Given such a potential, structural identification is not a process but an art-form, requiring the leveraging of sufficient experience and expertise for modeling, field testing, interpreting the data and improvement of the models. Each of the writers has pioneered modeling, field testing and structural identification of a variety of constructed systems, each accumulating heuristics over 4 decades.

In this paper the writers first articulated the state-of-the-practice of civil engineering and the pressing reasons for greater applications of structural identification to properly selected constructed systems. They continue with the history of structural identification as well as the challenges and opportunities facing this art in the 21st Century. As the writers became the carriers of the torch following an earlier generation of visionaries who laid the foundations of this art, they believe that this paper would serve to distill their decades of experience and heuristics for the future generations. We are slightly over length and hope that you will accept the manuscript based on its potential benefits for the civil engineering profession.

With best regards,

A. E. Aktan and J. M.W. Brownjohn

Sincerely,



A. E. Aktan PhD



24 *storefronts and basements for blocks around, 40 residents were evacuated, hundreds of offices and*  
25 *businesses were closed, subways were halted, traffic was rerouted and gas, water, electric, steam heat*  
26 *and telephone services were disrupted for many (NY Times, Jan 3, 1998).*

27

28 Three infamous 21<sup>st</sup> Century examples further demonstrate the unexpected cascading consequences of  
29 infrastructure failure:

- 30 • In the case of the World Trade Centre collapse on 9/11/2001, while airplane impact was a design  
31 consideration for the Towers, consequential explosion and fire associated with an airplane impact  
32 were neglected in the design. Catastrophic and disproportionate collapse of the Towers due to fire  
33 at the upper floors was completely unexpected. The NIST investigation (2005) into the collapses  
34 led to new code provisions.
- 35 • In the City of New Orleans on 8/31/2005 the storm surge due to Hurricane Katrina caused more  
36 than 50 breaches in drainage canal levees and also in navigational canal levees and precipitated the  
37 worst engineering disaster in the history of the United States. Such an event had been expected,  
38 but the neither the consequences nor the preparation needed for effective emergency response  
39 were properly estimated (ASCE, 2007).
- 40 • An hour after the 3/11/2011 Tohoku earthquake off the coast of Japan, the tsunami wave breached  
41 the protective walls at the Fukushima Nuclear Power Plant and destroyed the backup diesel power  
42 systems, leading to partial meltdowns at several reactors. The diesel generators were situated in a  
43 low spot on the assumption that the tsunami walls were high enough to protect against any likely  
44 tsunami. Subsequently ancient stone markers indicating higher Tsunami events were reported (CBS,  
45 2011).

46

47

## 48 **A Perspective on Infrastructure Performance in 2012**

49

50 One question civil engineers ask after each hazard is how we can better prepare for mitigating risks  
51 arising due to the failures of infrastructures to perform. For a successful civil engineering education and  
52 practice in the 21<sup>st</sup> Century, we have to learn how to consider the society, the built environment and  
53 nature as an integrated **complex multi-domain system** even if we may only be designing a light-post.  
54 Civil engineers have to leverage information, simulation, experimental (sensor), and decision technology  
55 more effectively and in an integrative manner, so that we may leverage innovative paradigms such as  
56 **lifecycle cost, sustainability, resilience, performance-based engineering, and risk-based asset**  
57 **management** accounting for the multi-domain systems nature of infrastructures (Hansman et al. 2006;  
58 Gurian et al. 2009; Moon et al. 2009). While the empirical-heuristic knowledge base of civil engineering  
59 served us well until early 20<sup>th</sup> Century, in the 21<sup>st</sup> Century we have to make design, operation,  
60 maintenance, and renewal decisions based on complete scenarios and analyses by leveraging complete  
61 and mechanistic models of complex systems and by properly interpreting relevant, objective data.

62

63 A new National Research Council Report (2011) noted that the absence of major earthquake in Urban  
64 USA has *lulled people into a false sense of security that the nation already is earthquake resilient. It*  
65 *noted a Los Angeles 7.8 magnitude earthquake simulation exercise and the staggering (simulated)*  
66 *consequent losses, and the lack of disaster resilience demonstrated by Hurricane Katrina. Natural*  
67 hazards with long return periods (500-2500 Years) and which are sometimes characterized as **black**  
68 **swan events** (Taleb 2010) are not the only concern related to infrastructure performance. In dense  
69 urban areas such as the Northeast Corridor in the US, transportation, water, power and communication  
70 are already failing to provide reliable and efficient operational performance under normal conditions

71 **every day**. There is ample concern for the safety and resiliency of the land transportation infrastructure  
72 under regular operating conditions **even without a natural or manmade hazard**.

73

74 The annual \$200 Billion cost to the US economy of transportation system (Mineta 2006) compounded by  
75 other hidden costs due to poorly performing infrastructure far exceed the cost of a major earthquake or  
76 hurricane with a 475-Year return period. Unfortunately, transportation planning and funding in the US  
77 today appears to be driven by “deficit reduction” rather than innovative enhancement of infrastructure  
78 performance and mitigating hidden costs of such **neon-swan events** (Zweig 2011) that are blindingly  
79 obvious and immensely important.

80

81 Many policy experts are advocating privatization mechanisms with users paying the cost of  
82 infrastructure services, such as Public-Private Partnerships (PPP) in order to finance future  
83 transportation funding. Primary requirements for attracting such investment are managing the risk of  
84 project delivery cost, lifecycle cost, and the reliability of performance, requiring a measurement of  
85 performance. Unfortunately, we still lack basic metrics for the valuation of infrastructure services and  
86 objective measures of performance.

87

88 Making effective investment and management decisions for multi-domain infrastructure systems is an  
89 increasingly complex challenge for which traditionally trained engineers are ill-equipped. ASCE’s Vision  
90 2025 (ASCE 2009) articulated the significance of the future civil engineer’s role in this relation and  
91 recognizes that most of the built environment in our densely populated cities has reached and exceeded  
92 design life and capacity. We can no longer think of civil engineering as designers of new constructed  
93 systems but rather as the caretakers and maintainers of existing infrastructures – i.e. **the architects of**  
94 **existing (and often geriatric) infrastructures – a role that is quite different from any that they have**

95 ***played in the past.*** This is a daunting challenge that the current practice of civil engineering and  
96 construction cannot expect to meet without renaissance. As development of printing technology  
97 facilitated the 15<sup>th</sup> Century *Renaissance*, ours will be facilitated through the applications of paradigms  
98 such as structural identification, health and performance monitoring, performance-based engineering,  
99 and asset management (Aktan et al, 2007; Moon et al. 2009).

100

## 101 **Objectives**

102

103 The term “structural identification” is an adaptation of the “system identification” concept from systems  
104 and control engineering to structural engineering of constructed systems. The term refers to a  
105 mechanistic “characterization” of a constructed system in terms of a physics-based analytical model.

106

107 Although civil engineers have been constructing both scaled physical and idealized physics-based  
108 analytical models for new design and construction since the Renaissance, they did not always realize the  
109 limited reliability of these. In fact, Galileo’s failure to estimate correctly the stress distribution in a beam  
110 is a well-known example (Ballarini 2003). Through the later part of the 20<sup>th</sup> Century, many civil engineers  
111 used computers and structural analysis software to construct 3D FE models, expecting to obtain more  
112 reliable predictions of structural behavior. As it was well-known and articulated by many 20<sup>th</sup> Century  
113 master structural engineers (Pier Luigi Nervi, Robert Maillart and Hardy Cross, amongst others), it was  
114 the collaborative US-Japan earthquake engineering research in the 1980’s that starkly revealed how  
115 typical approaches to modeling buildings fail to simulate critical behaviors of even highly idealized and  
116 symmetric 3D building systems (Bertero et al. 1984). Subsequent studies showed the importance of  
117 using experimental data measured in the field in order to seed analytical models to improve the  
118 reliability of simulations (Ghaffar and Housner 1976; Beck and Jennings 1980; Aktan and Farhey 1996;

119 Aktan et al. 1997; Aktan et al. 1998). These experiences revealed that discrepancies in the predicted  
120 versus measured global responses of a constructed system may easily exceed 500% and in the case of  
121 local responses may exceed 1000%.

122  
123 Today, it is clear that our inability to predict structural performance is not due to a lack of computers or  
124 software, but a lack of our ability as civil engineers to model a given structure-foundation-soil (SFS)  
125 system **completely** such that all the critical kinetic and kinematic mechanisms are incorporated at the  
126 linear and nonlinear regimes. If such a **complete** physics-based model is constructed, simulations may  
127 be used to estimate a demand envelope for a given load effect. Case simulations point out that the  
128 structure may be loaded to its nonlinear limit states, the complete linear model serves as an excellent  
129 starting point to construct one for nonlinear simulations. **Structural-identification provides a most**  
130 **effective way to improve reliability in computer modeling by reconciling experiment and analysis. St-**  
131 **Id may also help shape a realistic mind-model for all engineering and management disciplines since**  
132 **the concept leads us along a path to understand the reality of complex multi-domain infrastructure**  
133 **systems.**

134  
135 The greatest challenge in successful applications of St-Id (Moon and Aktan 2006) have emerged as the  
136 systems integration requirements, requiring mastery in management, modeling and simulation,  
137 experimental arts, information technology, and decision-making. Unless we understand how  
138 infrastructures perform as complex systems we cannot expect to formulate effective policies, strategies  
139 and project-specific designs for improving their performance as systems. **The authors' objective in**  
140 **writing this paper is to review the challenges that have to be overcome for successful applications of**  
141 **St-Id for serving condition, safety (vulnerability), serviceability, and reliability evaluation of a**  
142 **constructed system, as well as its health monitoring and management. The authors will further offer**



143 *recommendations regarding how we may reach the future potential of St-Id in concert with additional*  
144 *systems engineering concepts for the sustainable management of multi-domain infrastructures.*

145

## 146 **Overview of Current Best Practice for St-Id**

147

148 Since Prof. Yao and his colleagues published their pioneering ASCE work describing structural  
149 identification (Hart and Yao 1977; Liu and Yao, 1978), there has been extra-ordinary progress in  
150 computers, sensors, data acquisition hardware and software, and many St-Id applications. We recall that  
151 St-Id of constructed systems was first explored in conjunction with earthquake engineering research on  
152 the dynamics of buildings, nuclear facilities and dams by vibration generators, pioneered by Hudson in  
153 the early 1970's. Ghaffar's PhD dissertation at CALTECH (1976) advised by Housner, and their  
154 subsequent studies on the Golden Gate Bridge were early and remarkable efforts towards applications  
155 of structural identification. Subsequently, the earthquake engineering community became interested in  
156 using this concept for the identification of the dynamic characteristics of building structures from  
157 acceleration responses captured during earthquakes, and early studies on this theme were first reported  
158 by Yao (1979) and by Beck and Jennings (1980).

159

160 Douglas and Reid (1982) were early pioneers in applying the St-Id concept to characterize the lateral  
161 response characteristics of an actual highway bridge by pull-release testing. Following the publication of  
162 the Proceedings of Natke and Yao's 1987 workshop "Structural safety evaluation based on system  
163 identification approaches (1988)," the concept eventually attracted the interest of large numbers of  
164 structural and earthquake engineering researchers. With the influence of International Modal Analysis  
165 Conferences (IMAC) starting in 1982, increasing numbers of mechanical, aerospace and civil engineering  
166 researchers became interested in taking advantage of vibration-based St-Id for testing and

167 characterizing structures such as offshore towers, highway bridges, towers and buildings (Beck and  
168 Jennings 1980; Bonato et al. 1997; Aktan et al. 1997; Aoki and Sabia 2005; Liu et al. 2005; Nagayama et  
169 al. 2005; Gentile 2006; De Sortis and Paoliani 2007; Morassi and Stefano 2008; Conte 2009). In addition  
170 to these authors and others referenced later in this paper, we acknowledge significant contributions by  
171 Shinozuka (2005), Farrar ( 1994, 1999, 2003), DeRoeck (2001 (a), (b)), Sanayei (1997), Betti (2004),  
172 Hjelmstad (2009), DeWolf (1999) with their students and collaborators to structural system  
173 identification from engineering mechanics, computational mechanics and experimental mechanics  
174 perspectives.

175

176 It is a significant accomplishment that the ASCE Committee reached consensus on SIX essential Steps  
177 that have to be integrated in a complete and successful St-Id application to an actual, operating  
178 constructed system. The integration of these Six Steps would not be in any strict order, depending on  
179 the system, problems driving St-Id, etc:

180

181 **1. Clearly establish a business case**, in conjunction with the drivers and specific objectives for a St-  
182 Id application and identify any critical constraints that may challenge its success. Collect and  
183 evaluate all available legacy data and information including heuristic domain knowledge about  
184 the constructed system. Construct an e-warehouse that will serve as a library for all the legacy  
185 and new material. Use building information modeling (BIM) and bridge management systems  
186 (BMS) to serve as e-libraries.

187

188 As very few owners, consulting engineers, and even large consulting companies may claim  
189 successful experiences with technology integration, it is both a challenge and a prerequisite to  
190 win an owners' and consulting engineers' support for access to for the St-Id of a constructed

191 system. Many owners prefer to delegate professional engineering work to consultants, and a St-  
192 Id application will often have to be approved and supported by the consultant who may be in  
193 charge of the inspection, maintenance, repair, or management of a facility.

194  
195 One obvious application for St-Id would have been in seismic instrumentation of buildings and  
196 bridges. For example the Strong Motion Instrumentation Programs by CA, USGS, Japan and  
197 Taiwan are currently NOT leveraging St-Id for optimum instrumentation design or reliable  
198 interpretation of strong motion data. With proper system design, informed by St-Id and  
199 complementing the typical accelerometer system with strain gauges and tilt-meters, the current  
200 investment into SMIP's may offer a greater payoff. The authors urge CSMIP, CALTRANS, USGS,  
201 US Army Corps and other agencies that are responsible for seismic instrumentation to explore  
202 the potential payoff from St-Id of a facility scheduled for seismic instrumentation.

203  
204 Infrastructure owners may be motivated to leverage St-Id if an application promises to save a  
205 portion of repair, retrofit, or renewal funds or at least ascertain the effectiveness of renewal if  
206 designed in a traditional civil engineering approach. St-Id may even help show the retrofit is not  
207 necessary at all (Moyo et al. 2004). For these purposes, a mechanistic understanding of the  
208 existing constructed system and its characterization, by a calibrated computer model, are  
209 critical. St-Id could also assist when visual inspections reveal performance concerns for large,  
210 critical constructed systems. Vibrations, cracking, deformations and drifts that exceed  
211 thresholds and lead to serviceability concerns require that root causes are identified and  
212 mitigation strategies identified (Brownjohn et al. 2010; Moutinho et al. 2011). These are best  
213 identified through a St-Id application.

214

215 St-Id may be a means of establishing a quantitative and mechanistic baseline characterization  
216 for a newly constructed system similar to a **birth-certificate**. Documenting the baseline  
217 mechanical characteristics is invaluable and in fact essential in the case of performance-based  
218 engineering. In the case of innovative financing and project delivery of infrastructures through a  
219 Public-Private Partnership (PPP) arrangement, documenting the mechanical characteristics of a  
220 system as it changes hands from one party to another provides a strong business case for St-Id.  
221 As PPP becomes an increasingly preferred mechanism, we expect to see a much greater  
222 emphasis by financiers, owners, concessionaires, and insurers for relying on mechanistic models  
223 based on field data. This would become a major driver for increased numbers of state-of-the-art  
224 St-Id applications during construction, at commissioning, and after any event that may have an  
225 impact on the lifecycle. Finally, some major infrastructure owners and consultants have  
226 developed an appreciation of the value of St-Id especially in relation to retrofit design and  
227 historic preservation. Examples include NY City long span bridges such as the Brooklyn Bridge,  
228 the Henry Hudson Bridge, and the Throgs Neck Bridge.

229

230 **2. Study legacy data and information.** Observe the system in the field under different operational  
231 and environmental loading conditions and conceptualize the system for a-priori modeling.  
232 Take advantage of practical measurements during field observations to capture as-is  
233 dimensions, material properties, and global structural characteristics such as natural frequencies  
234 and mode shapes. This step requires an ability to observe an actual full-scale system in the field,  
235 leverage heuristics, and decide on the characteristics, loading and response mechanisms – i.e.  
236 site, soil, foundation, load paths, displacement, deformation, and any concentrated distortion  
237 patterns; boundary, continuity, and movement systems - that should be incorporated in the a-  
238 priori model. Field observation offers the opportunity of reducing uncertainties about

239 operational response levels, and help shape the model to allow inclusion of condition and  
240 performance deficiencies.

241  
242 In the construction of a-priori models it is important to recognize that multiple models can  
243 represent a system (Goulet et al. 2010; Raphael and Smith 1998; Beven 2002). The model-  
244 builder has to have experience with constructed systems, as FE software will permit the  
245 construction of various models that may appear to simulate the geometry with fine resolution  
246 but still fall short of simulating the kinetics and kinematics. It is highly recommended to  
247 construct a model that can serve the objectives of St-Id at minimum necessary resolution.  
248 Mixed microscopic and element level models, representing critical details and regions in  
249 microscopic detail but represent less critical elements at an element level, may offer  
250 advantages.

251

### 252 **3. Operational Monitoring and Controlled Experimentation.**

253 ***There are several types of field experiments including:*** (a) ambient vibration testing (He et al.  
254 2009; Brownjohn 2002; Brownjohn et al. 2011), (b) forced excitation testing (Brownjohn et al.  
255 2003), (c) controlled load testing (Calcada et al. 2005), and (d) monitoring operational and  
256 environmental events (Catbas et al. 2008), with an St-Id campaign including one or more of  
257 these components with (a) or (b) more likely to be first, and (d) to run to the end. Application of  
258 (c) is already a requirement of a number of transportation agencies worldwide.

259

260 The a-priori model should be leveraged to design each type of experiment and especially the  
261 instrumentation required. Instrumentation should be designed to: (i) control the safe and  
262 successful execution of the experiment; (ii) test hypotheses regarding critical structural

263 behaviors and the root causes of any condition issues; iii) immediately assure data quality; (iv)  
264 serve as the basis for the model refinement and calibration step.

265

266 The information provided by various experiments in (a) to (d) complements each other: Ambient  
267 vibration testing over a day to several weeks provides average values and variations in the  
268 frequencies, mode shapes, and damping of various modes. Monitoring operational and  
269 environmental events over several weeks to several months provide average magnitudes and  
270 bounds of inputs and responses due to live loads, wind, temperature, radiation, and other  
271 intrinsic force mechanisms (Brownjohn and Pan 2008). These two experiments may be  
272 performed simultaneously (Pakzad et al. 2008). However, controlled load testing at proof-load  
273 levels in conjunction with properly designed instrumentation and data acquisition remains a  
274 most definitive manner of measuring critical behaviors of medium-span bridge structures.

275

#### 276 **4. Data Archival, Quality Assurance, Processing, Pattern Extraction, Modeling and Interpretation.**

277 This category has two sub-divisions, with the first three activities representing the basic  
278 minimum requirement and of themselves requiring an excellent computational engineering and  
279 IT background. Metadata and data need to be checked for quality assurance and archived prior  
280 to processing, preferably during the experiment, to catch and rectify mistakes in-situ.

281

282 Processing of dynamic and static data for extracting the mechanical properties of a system and  
283 patterns require a good signal processing and structural dynamics background. Technology  
284 advances in modal analysis facilitate on-site analysis of dynamic data for type (a) and (b) tests  
285 that can advise changes in experimental strategy in near real-time.

286

287 Pattern extraction, development of meta-models and interpretation are specialized fields that  
288 represent one of the most significant challenges for St-Id (Cross et al. 2010; Moaveni et al.  
289 2009). This activity cannot be carried out in isolation since the coordination, quality testing, and  
290 reality checking of any products from this Step, especially the physical interpretation of the data  
291 in relation to structural behavior and performance, require continuity, feedback, and iteration  
292 between all of the steps 1-4.

293

#### 294 **5. Selecting, Calibration and Validation of Physics-Based Model(s).**

295 Applied mechanics experts may worry that such a model cannot represent a structure-  
296 foundation-soil (SFS) system that may be nonlinear, non-observable and non-stationary. In fact a  
297 constructed system is never entirely observable or stationary, and many critical parameters and  
298 mechanisms are clouded by not only random but epistemic uncertainty (Oberkampf 2005).

299

300 Nevertheless, a calibrated and validated physics-based linear model for scenario analysis and  
301 decision-making is an essential St-Id tool for addressing structural engineering problems.  
302 Structural engineers are well-aware that a constructed system cannot be strictly linear, yet  
303 many limit states (e.g. excessive vibration) may occur within the linear performance range.

304 **The real challenge (and art) in St-Id an art is to know how and when to smear rationally all the**  
305 **nonlinearity and non-stationary characteristics of a system into a linearized, physics-based**  
306 **model that is suitable for the objectives of the St-Id application, while retaining a healthy**  
307 **degree of skepticism until the model is proven reliable.**

308

309 The size, resolution, and sophistication of a physics-based model depends on the objectives of  
310 St-Id, the consequences of the uncertainty in estimating demands, capacity, and vulnerability,

311 and on the critical failure modes of a SFS system. This model can never be unique or fully  
312 representative. However, with reliable and well interpreted performance data, it should be  
313 possible to leverage heuristics and reach a reasonable level of confidence in the ability of a  
314 model to represents important characteristics of the actual constructed system. This requires  
315 structural and geotechnical specialists to work more closely and adapt each other's technologies  
316 for model validation.

317  
318 While many exercises focus on variability of model parameters, the most critical problem in St-Id  
319 is to ascertain that a model is **complete**. It must incorporate all the critical force distribution  
320 mechanisms and the kinematics depending on boundary conditions, soil-foundation  
321 characteristics, and deformation patterns of elements or groups of elements. Incompleteness  
322 due to epistemic uncertainty (in addition to difficulty in 3D conceptualization) is often the most  
323 significant source of model error, and it is extremely difficult to identify such errors unless each  
324 step of St-Id is coordinated and performed as a continuum.

325  
326 Identifying a model that is complete is a challenge in every discipline. We should ideally explore  
327 an infinite space of possibilities then rule out spaces of variables for which the model is not  
328 compatible with observations. In fact the best we can do is to find a model that is **compatible**  
329 with measurement data and noise levels as well as with the application.

330  
331 We inject some caution: The calibrated or updated model should be a projection of complete  
332 behavior on the space of observable signals and information. In that sense it can be dangerous  
333 to attempt to apply it to gain new knowledge that it does not contain (Brown 1985). This is  
334 analogous to the danger of extrapolating from data that are only robust to interpolation.



335 **6. Decision-Making**

336 *Step 6 involves leveraging the calibrated model for scenario analyses, evaluating, and*  
337 *prioritizing decisions regarding the performance and/or condition concerns, and/or retrofit*  
338 *and renewal design.* Critical risks due to probable non-performance of the system at any limit-  
339 state should be identified in this stage. Critical hazards, vulnerabilities, and probable failure  
340 modes need to be identified, validated and documented as an objective overview of the health  
341 of a system in order to strengthen the business case for St-Id.

342  
343 The key to a successful culmination of St-Id is therefore whether the calibrated model proves  
344 suitable for comprehensive scenario simulations – especially related to the safety and stability of  
345 failure of the facility due to various manmade and natural multi-hazards. Reliably simulating  
346 phenomena such as blast, fire, impact, accident, flood as well as operational and serviceability  
347 concerns may require more than one model or one software package. Finally, during each of  
348 the Steps 1-6, coordinators of St-Id should be leveraging heuristics to a maximum, and Step 6  
349 should certainly include the owners and managers of the system.

350

351 **Implications of the Overview for Best Practices**

352 A successful outcome of St-Id very much depends on each of the steps being accomplished successfully  
353 *within a continuum* as opposed to in isolation. In the past there have been attempts to carry out these  
354 six steps sequentially by different specialists working like a tag team. These efforts have not been as  
355 successful as applications where the entire cycle would be coordinated by the same person, allowing for  
356 iteration of the whole cycle or parts of it. Such a person would have experience in the six steps and be  
357 able to integrate mind-model views of the same system from:

- 358
- Owner/operator

- 359 • Consulting engineer
- 360 • Modeler - integrating analytical, mathematical, numerical and computational modeling
- 361 • Experimentalist - designing and executing field experiments to capture the critical system behaviors
- 362 • Risk and reliability analysis and optimization expert to judge and correlate analysis and experiment
- 363 • Expert manager to integrate empirical-heuristic knowledge with the objective-mechanistic insight
- 364 from St-Id to make informed management decisions

365

366 Present day civil engineering courses provide very little training for such a role. Hence one of the major  
367 challenges in introducing the St-Id approach advocated here is to advise accreditation agencies  
368 worldwide that they should require universities to switch from a culture of structural engineering  
369 teaching focusing on designing for new structures to one of maintaining and managing our existing  
370 infrastructures. This fits perfectly within the popular ethos of resilience and sustainability. We can also  
371 show students and engineers they can have more fun figuring out how an existing structure works than  
372 designing a new one.

373

374 It is important to identify requirements for St-Id to provide sufficient payoff. First, the owner/manager  
375 of a constructed system should be entirely convinced of the necessity of St-Id for making prudent  
376 management decisions. Second, the St-Id team of *coordinator* and specialists must be available and  
377 should possess the empirical-heuristic knowledge that can only come from experience over many  
378 decades of field work on actual constructed systems. If these requirements are not met it is best not to  
379 expect much from St-Id. Even when the second requirement is met and a large investment is made in  
380 St-Id, confidence bounds in identifying such parameters as global flexibility, mode shapes, local  
381 deformations, movements and reactions of a large system such as a long-span bridge can only be as

382 good as 75%-90%. Hence operators/owners are justified to be skeptical, reinforcing the need to identify  
383 clearly, situations when a payoff can be had from St-Id:

384 1. When we step outside the bounds of applicability of codes and design for innovative structural  
385 forms and/or new construction methods and materials, we have to rely on St-Id to mitigate the risks  
386 due to epistemic uncertainty.

387 2. When we have an existing constructed system whose operation is vital for the well-being of an  
388 urban region, and the system is exhibiting distresses and performance concerns such as excessive  
389 vibrations, cracks, spalls, etc. then St-Id should pay off.

390 3. In the case of constructed systems that may be managed as a fleet, e.g. simple highway overpasses  
391 designed and constructed with highly similar materials, St-Id of a select sample may help manage a  
392 much larger population more effectively.

393  
394 The value in a properly executed St-Id would be a more reliable and complete conceptualization of i) the  
395 performance of a constructed system ii) its critical regions and behavior mechanisms (e.g. force paths  
396 and kinematics), and iii) its critical loading scenarios and the estimation of its failure modes under  
397 extreme events. St-Id would also support formulation of strategies for effectively mitigating  
398 performance deficiencies. Given that even well executed St-Id may cost between \$50K and \$1M  
399 depending on the size, complexity and resolution; the potential for saving insurance and replacement  
400 costs, the criticality of the functions of a constructed system, and expected lifecycle must all be factored  
401 into the cost-benefit analysis when making a business case for St-Id.

402

403

404

405

## 406 **Towards System-Identification of Complex Multi-Domain Systems**

407

408 The current state of the art on St-Id of constructed systems has been documented in a Report by the  
409 ASCE SEI Committee on St-Id of Constructed Systems (ASCE-SEI 2011). This report contains an overview  
410 of more than 15 contemporary St-Id applications, including those of tall and midrise buildings, towers,  
411 suspension bridges, long-span arch and truss bridges, and movable bridges. A wide range of  
412 experimental tools, from ambient vibration, wind, seismic monitoring, forced excitation, impact, and  
413 truck-loading have been used. Physics-based models of various resolutions, including macroscopic,  
414 element level and microscopic Finite Element models were used for the simulation of these constructed  
415 systems. Many other applications that leveraged non physics-based models have also been discussed  
416 and referenced in the ASCE Report.

417

418 As evidenced by the applications to real buildings, bridges, and towers detailed in the ASCE SEI  
419 Committee Report by Kijewski-Correa and Kareem, Omrani and Taciroglu, Ni, Moaveni, He and Conte,  
420 Zhang, Pan, Prader and Moon, Pakzad and Fenves, Yun and Masri, Fujino, Siringoringo and Nagayama,  
421 Goulet and Smith, Catbas and Gul, Schlune, and Plos and Gylltoft, we may estimate the existence of  
422 more than two dozen centers of excellence in the world that can presently do justice to the challenges  
423 of St-Id applications to large constructed systems. Meanwhile, there is increasing evidence that  
424 modeling and simulation of just constructed systems are often insufficient to reach reliable decisions for  
425 architecting and managing our built environment.

426

427 Management of multi-domain systems require decision-making at the confluence of natural, social, and  
428 engineered domains, and no matter how reliable we may model the engineered components of  
429 infrastructures, we still need to incorporate social factors such as politics, policy, economy,

430 sustainability, etc. in most decisions. It follows that whether we may expand the St-Id concept to the  
431 system-identification of complex multi-domain systems such as infrastructures becomes a highly  
432 important question.

433

434 As an example of a complex multi-domain system, consider the highway transportation infrastructure.  
435 Many engineers and users may envision this system as comprised of roads, bridges, signs and traffic.  
436 However, as Fig. 1 provides a depiction of the actual system comprised of complex, mixed and  
437 intertwined layers of **Human, Natural** and **Engineered** Systems and Elements. The Human systems  
438 would include societal (history, culture, values, politics, policy, economy), organizational, institutional  
439 (as well as corporations), and individuals. Natural systems include climate, weather, geology-soil, water,  
440 air, plants, and animals. Engineered systems include manufactured elements such as autos, signals,  
441 lights, signs, ITS cameras and communications, enforcement, and security systems. Finally, constructed  
442 elements include pavements, bridges, retaining walls, drainage structures, embankments, sound-  
443 barriers, sign structures, etc. The system is highly dynamic, non-stationary, and multi-scale; affected by  
444 phenomena and mechanisms at microscopic thru macroscopic length scales as well as along a very long  
445 frequency bandwidth, from under 0.1Hz thru Giga-Hertz levels. Such systems need to be explored and  
446 mapped with all sub-systems and elements from various domains, along with the intersections,  
447 interdependencies, and interactions between these at various performance limit states and time.  
448 Contributions by Sussman (2005) towards a process for studying such systems, which he has termed:  
449 **“Complex, Large-Scale, Interconnected, Open, Socio-technical (CLIOS) Systems”** are noteworthy.

450

451 Figure 1 shows how little means we have for knowing how to perturb and control such a CLIOS system  
452 optimally and effectively (through policy, planning, financing, revenue generation and management  
453 paradigms, decisions and actions) so that we may get outcomes which we desire such as acceptable

454 performance levels in conjunction with minimum lifecycle cost. The hypothesis is that if we are able to  
455 model and identify such a system, with its most critical human, natural, and engineered elements, we  
456 may formulate planning, financing, revenue, operational, and maintenance/preservation management  
457 policies that may offer an optimum performance of the entire system for maximum lifecycle  
458 benefit/cost. Given the considerable debate that is currently ongoing for various financing, revenue,  
459 and ownership mechanisms for critical infrastructures, especially regarding the financing of essential  
460 infrastructure services, a clear understanding of the system would be invaluable in order to identify  
461 cause-and effect relationships that may result from various acceptable options for such decisions. Policy  
462 and planning would be founded on a much more realistic and objective understanding of the entire  
463 system rather than driven by political convenience.

464

465 It is especially challenging to understand and model various human systems such as organizations,  
466 corporations, institutions, and individuals as well as their communication and decision-making  
467 processes. Various investigators have proposed macro-modeling approaches based on economic and  
468 network models. There have also been simulations of individuals and populations based on “agent  
469 models” (Kai et al. 1998; Sharpanskykh and Stroeve 2011; Hersey 2001; Bonabeau 2001). Organizational  
470 and process models have also been proposed (Popova and Sharpanskykh 2008). For example, Figure 2  
471 depicts a stakeholder influence diagram for evaluating how various institutional and policy decisions  
472 may impact management decisions for a toll-bridge system (Jackson et al. 2011). The fact remains that  
473 the state of practice for reliable modeling and simulation of multi-domain systems, especially the  
474 Human systems and elements within these systems is in its infancy. Coordinated research and  
475 demonstrations by multi-disciplinary teams, including social scientists, economists, finance and business  
476 managers as well as a new generation of civil and environmental multi-domain systems engineers are  
477 urgently needed for enabling sound and prudent policy decisions regarding infrastructures.



479 **Conclusions:**

480

481 Structural-system identification after four decades came of age as a mature civil engineering concept  
482 applicable to any constructed system (provided a sound business case can be made for it). The concept  
483 requires a coordinated, integrative multi-disciplinary effort, bringing together most of civil engineering  
484 sub-disciplines in addition to electrical and mechanical engineering expertise. Application of the concept  
485 to a constructed system results in a characterization of the system through a physics-based  
486 (mechanistic) model. An infinite number of models can be constructed to represent a constructed  
487 system at many levels of detail (resolution) and complexity (distributed, nonlinear and/or stochastic).

488 **The challenge is to pick the minimum levels of resolution and complexity justified for a given system**  
489 **and the objectives driving the St-Id.** The remainder of the St-Id is then focused on making this model  
490 “complete” and error-free, then to assign confidence bounds for simulations of the system subjected to  
491 the scenarios relevant to the St-Id application objectives.

492

493 Given that the single most critical barrier to confidence in simulations involving constructed systems is  
494 the *epistemic uncertainty* associated with the as-is mechanical characteristics and various capacities of  
495 the system, its foundations and soil, as well as its remaining lifecycle, and the demands anticipated  
496 during this period, the authors do not endorse unnecessary sophistication in modeling or in trying to  
497 simulate randomness in those common parameters in a FE model without an abundance of data  
498 required for characterizing randomness. The single most important requirement is to make the model  
499 and simulations *sufficiently complete*, i.e. incorporating all of the critical mechanisms that may govern  
500 the kinetics and kinematics as well as proper choice of the scenarios that will be simulated by the model  
501 given the drivers of the application.



502 The challenge of constructing a “*sufficiently complete*” model brings to us the necessity of incorporating  
503 heuristics about the type of constructed system and anything that is known about the specific system  
504 being identified. Also critical will be the ability to observe and conceptualize a constructed system –  
505 requiring the model builder to actually see, touch, and observe the system for days if not weeks; in  
506 addition to studying plans, drawings and other documentation and leveraging visualization tools for  
507 completely conceptualizing the 3D geometry.

508

### 509 **Recommendations:**

510

511 The authors recommend that skilled groups that have demonstrated expertise in St-Id of constructed  
512 systems remain connected, and continue demonstrating best practices while exploring ways to improve  
513 the reliability to be expected from St-Id applications through round-robin studies. One such study has  
514 been initiated by the authors by leveraging a common highway bridge in NJ, under FHWA and NJDOT’s  
515 support and auspices (A. Aktan et al., unpublished LTBP report 2011).

516

517 There is an urgent need to increase the number of civil engineering academic programs that are capable  
518 of demonstrating and teaching St-Id.-We urge the numerous civil engineering programs to develop field  
519 research capabilities and include St-Id as a component of their curricula in the near future. We also urge  
520 that accreditation agencies such as ABET (USA) and JBM (UK) require inclusion of St-Id in civil  
521 engineering curricula. Given that measurements, experiments, data interpretation, analysis and design  
522 are all already expected to be included in the elements of a modern civil engineering curriculum, their  
523 teaching could be linked using the St-Id concept for a more rewarding student experience (Yao 1996).

524

525 Federal government agencies such as NIST, NSF, FHWA and others should consider St-Id as an important  
526 enabler for meaningful technology integration and generation of fundamental knowledge. The more  
527 applications reveal hidden behaviors and common blind-spots in modeling constructed systems, the  
528 more we will be able to characterize constructed systems with mechanistic models of improved  
529 confidence. The risks associated with modeling critical constructed systems without any understanding  
530 of the confidence in the simulations have become too great in dense urban areas where the  
531 consequence of failures and even delays in a project have become unacceptable.

532

533 A final recommendation regards urban infrastructure rejuvenation, which is an essential element and in  
534 fact a driver of urban rejuvenation. Presently there is no established integrated systems approach to  
535 infrastructure planning, feasibility, sustainability analysis, design, construction, operation, and  
536 management, providing an opportunity to map the St-Id concept for modeling entire infrastructures in  
537 manners that may be validated. Current infrastructure modeling approaches are generally macroscopic,  
538 e.g. network and macro-economic models, while there have been efforts towards simulating the human  
539 and organizational elements of infrastructures for transportation planning, none of which approaches  
540 have matured or been properly validated.

541

542 Structural engineers should coordinate research in integrative modeling of infrastructures along with  
543 their societal, organizational and individual human elements, nature and environment in addition to  
544 their engineered systems. This will require use of actual transportation (highway, airport, rail, transit,  
545 etc.), water and power distribution networks as real-life laboratories. 'Infrastructure' is becoming a  
546 pressing "hot" research area and structural engineers need to seize opportunities to steer research  
547 funding agencies and foundations towards funding real-life field laboratories for research, education,  
548 and demonstrations of infrastructure modeling and system-identification. Experience from such live

549 laboratories will develop understanding of complex, multi-domain (CLIOS) systems, empowering  
550 structural engineers to transform management decision-making based on realistic scenario simulations.

551

552

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736 [http://en.wikipedia.org/wiki/2011\\_T%C5%8Dhoku\\_earthquake\\_and\\_tsunami#Nuclear\\_power\\_plants](http://en.wikipedia.org/wiki/2011_T%C5%8Dhoku_earthquake_and_tsunami#Nuclear_power_plants)

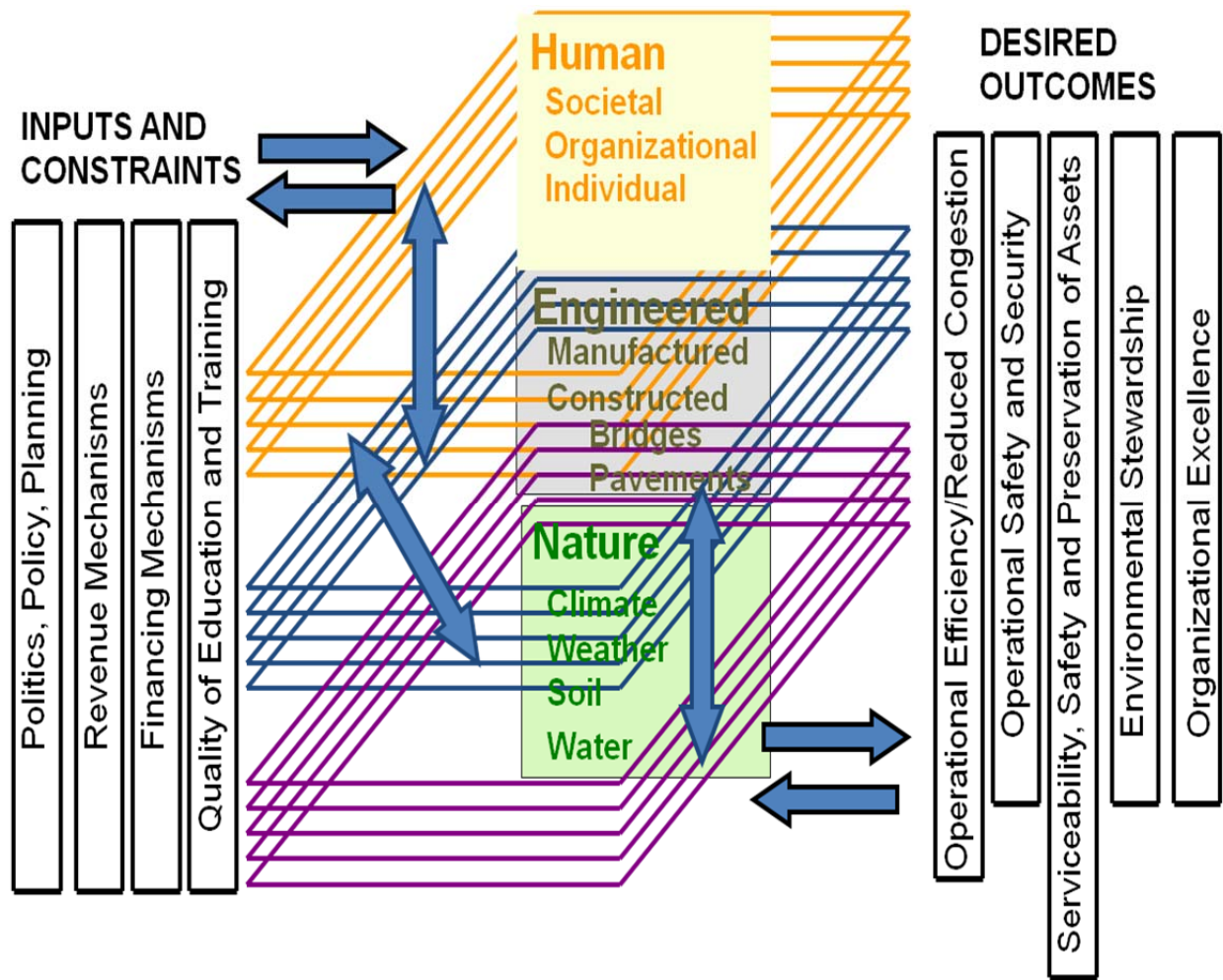


Figure 1: A Multi-Layered Representation of the Highway Transportation System

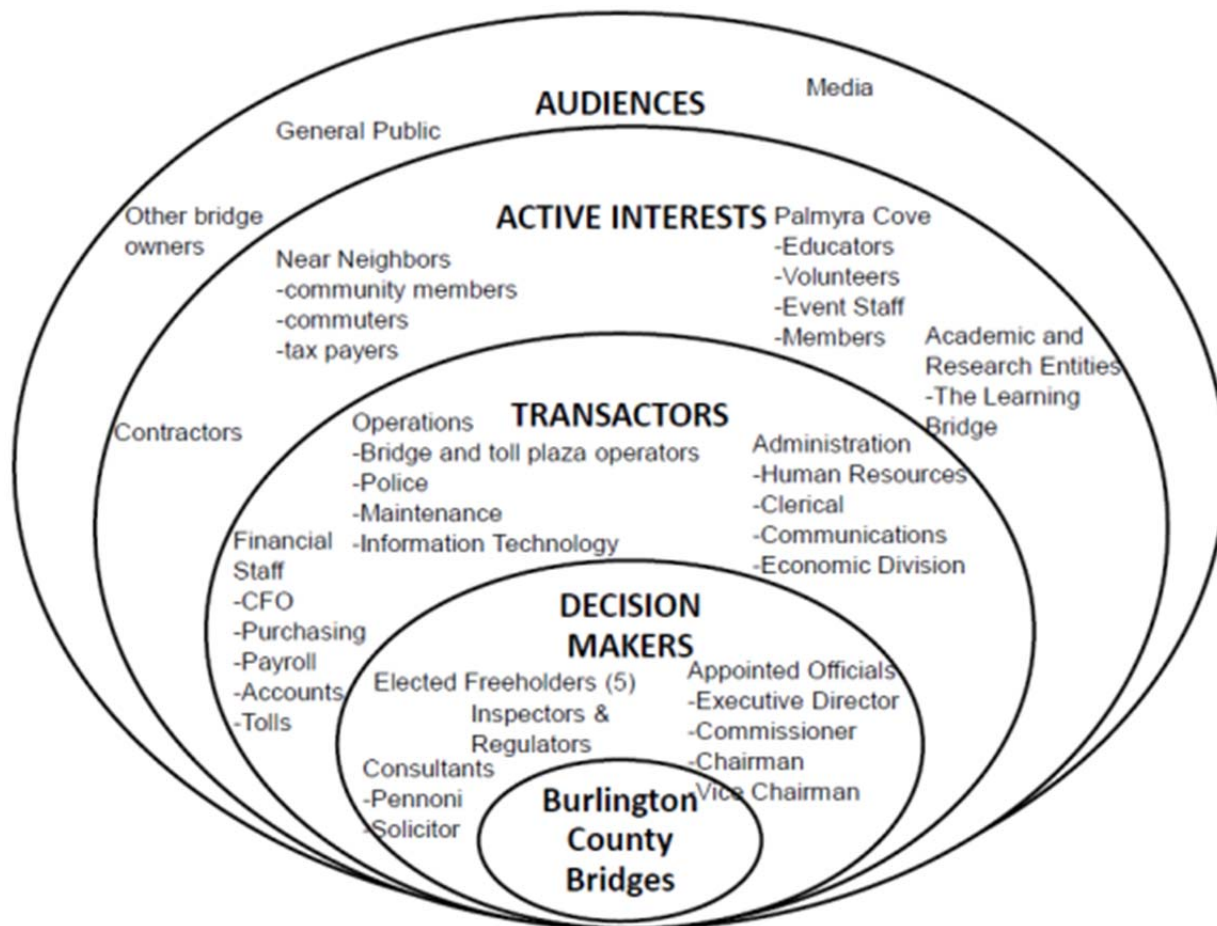


Figure 2: Schematic Representation of the Stakeholders of a Toll Bridge

# LIST OF FIGURE CAPTIONS

Figure 1: A Multi-Layered Representation of the Highway Transportation System

Figure 2: Schematic Representation of the Stakeholders of a Toll Bridge



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**Corresponding Author Name and Address:** Ahmet Emin Aktan, 50 Belmont Avenue Unit 1010  
Bala Cynwyd, PA 19004

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To: Editorial Board of Journal of Structural Engineering

Manuscript Submission- Structural Identification: Opportunities and Challenges

Dear Editors,

The referenced manuscript was submitted to the Journal, and following its review, revisions were suggested. We are grateful for these suggestions and implemented them.

Here we would like to submit the captioned *revised* manuscript as a FORUM PAPER to the Special Issue of the Journal of Structural Engineering on Structural Identification for your consideration. The first author of the manuscript is Dr. A. Emin Aktan and the Co-author is Dr. James Brownjohn. The corresponding author is Dr. Aktan and the contact information is below for your reference.

Discussion of the SIX STEPS has been reduced - however, the remaining discussion is not thought to be repeated in the other reports. The discussion is based on the personal experiences of two highly experienced "senior citizens" that are not necessarily shared by the younger generation.

This paper exceeds the 5,000 word limit. However, The FORUM Paper was invited by the Guest Editors to offer an overview of the concept from its origins to current state of art. The concept of St-Id holds so much promise for enhancing the performance of constructed systems and for reforming civil engineering education that we submit that there is value to increase the word limit.

Address: Drexel University  
CAEE Department  
3141 Chestnut Street  
Philadelphia, PA, 19104

Tel: 215-895-6135  
Fax: 215-895-6131  
E-mail: aaktan@drexel.edu

Best Regards,  
A.Emin Aktan  
Roebing Professor of Infrastructure Studies  
Department of Civil, Architectural and Environmental Engineering  
Drexel University  
Philadelphia, PA 19104