by means of curve fitting are suitable for a specific location and environmental characteristics such as wind speed (Meira *et al*. 2003; Hossain and Easa, 2011). To build model for determining the dry deposition of chloride for different coastal regions with varying wind speed of Bangladesh, similar distances from the shoreline (10, 100, 200, 500 and 1000 m) as of Eq.1 (Meira *et al.*, 2008) are adopted. Relationship between v_{dep0} and v (for $v \geq 3$ m/s) is given in Eq. 2.

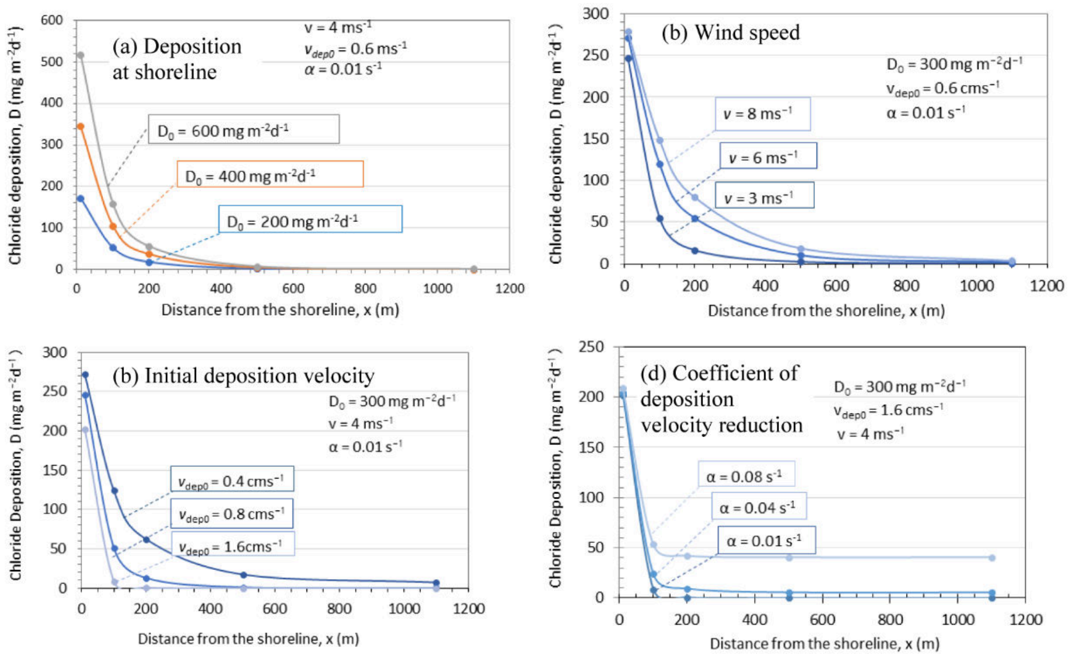

Figure 2: Sensitivity analysis of the model (Eq 1).

$$v_{dep0} = 7.215e^{0.0513v} - 7.29 \qquad R^2 = 0.811 \qquad \text{(Eq. 2)}$$

Considering the average wind speed $v = 4.6$ m/s during the study (Hossain and Easa, 2011) Eq. 2 gives $v_{dep0} = 1.85\,cms^{-1}$. Then relationship between $\boldsymbol{v_{dep0}}$ and α given by Meira *et al.* (2006) is used to calculate α for coastal zone of Bangladesh.

$$\alpha = 0.01387\left(e^{v_{dep0}^{0.9205}} - 1\right) \qquad R^2 = 0.751 \qquad \text{(Eq. 3)}$$

Considering, $\boldsymbol{v_{dep0}}$ = 1.85 cms^{-1} in Eq. 3, α becomes 0.067. Now considering the values of D_0, v, v_{dep0} and α as 200 mg m^{-2} day^{-1}, 4.6 m/s, 1.85 cms^{-1} and 0.066 respectively in Eq. 1, the dry deposition result of chloride from the model is found close to the literature. However, beyond 100 m the dry deposition value of chloride deviates from the field data and again matches between 600 to 800 m. After multiple trial and error values of D_0, v, v_{dep0} are found 220 mg m^{-2} day^{-1}, 4.6 m/s, 1.31cms^{-1} respectively when α values ranged between 0.03-0.038 s^{-1}. For α = 0.038 s^{-1} gives the dry deposition of chloride close to model. Figure 3, shows that the deposition values found from the model is slightly lower than the actual data up to 100m from shoreline. Beyond 100m, the dry deposition value of chloride is almost similar to the field data and can be used to estimate chloride level at different distances from sea. The simplified proposed model for Bangladesh is given in Eq. 4,

$$D = 220e^{3.447\left(e^{-\left(0.038\,x/v\right)} - 1\right)} \, [mg\ m^{-2}day^{-1}] \qquad \text{(Eq. 4)}$$

Where, D is the salt deposition on the testing device at a distance x from the shoreline and v is the wind speed. This model shows a clear reduction of chloride in the first meters from the shoreline, due to the gravimetric settlement of salt particles.

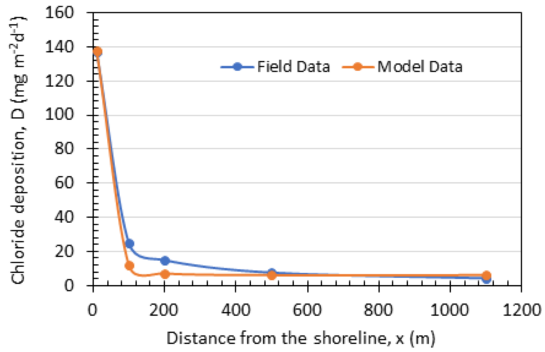

Figure 3: Calibration of model with respect to field data.

Exposure class for Bangladesh for corrosion induced by airborne chloride

The Draft BNBC does not specify the distance from seawater to be considered as coast. Ramalingam and Santhanam (2012) suggested that distance up to 10 km to be treated as coast while AS 3600 considered inland beyond 50 km of coastline. Other researchers from different countries (Haque *et al*. 2005; Meira and Andrade, 2013) show that, 100 m from shore line could be treated as the most severe zone. High deposition rate of sea salt on concrete structure is significant up to 200 m from sea shore in Chittagong, Bangladesh (Hossain and Easa, 2011).

Based on the experimental outcome and numerical simulations, Meira and Andrade (2013) gave chloride deposition on concrete structures situated within 100-750m ranging 100-10 mg/m^{2}day^{-1} for a service life of 50 years. In that case a minimum 30mm clear cover with a maximum w/c ratio of 0.50 was proposed. Based on the experimental outcome by Hossain and Easa (2011), researches mentioned above, international codes and classification of airborne salinity suggested by ISO 9225 and Meira and Andrade (2013), the exposure classifications of Bangladesh for corrosion induced by air borne chloride is proposed. Where, CL1, CL2 and CL3 are defined as Low, Moderate and High aggressiveness with Chloride deposition rates <10, 100-10 and >100 mg/m^{2}day^{-1} at beyond 1 km, within 0.1-1 km and 0-0.1 km distances from the coast respectively. The exposure classes are shown in Figure 5-a. Red, yellow and green color represents high, moderate and low aggressiveness level respectively.

Exposure classes for Bangladesh- Submerged, Tidal, Splash and Spray Zones

The degree of chloride ingress is sensitive to the environmental conditions. Particularly, in the splash and spray zones where contact between concrete surface with the seawater is more random than concrete in the tidal zone. In the tidal zone, concrete surface remains in a saturated or near-saturated condition (Kim *et al*., 2016). For this analysis CTL of 0.4% and 2% by weight of cement is considered for tidal and splash zone and for submerged zone. Figure 4 shows the depths service life combination at which the critical chloride concentration is reached.

Researches (Angst *et al*., 2009; Kim *et al*., 2016) considered CTL as 2.0% by weight of cement for submerged zone. Kim *et al*. (2016) studied chloride transport behavior in concrete subjected to tidal, spray/splash and submerged zone similar to the exposure conditions defined as XS3 and XS2 in EN 206. The amount of chloride ingress in concrete is determined biannually over the initial 8-years exposure and the study was conducted for approximately 20 years. Using these data a relationship between time of exposure and depth at which CTL reached is developed (Figure 4-a). Considering 50 and 100 years of exposure for concrete (w/c=0.40), the CTL was found to reach at 63 mm and 73 mm depths respectively. British Standard (BS 8500-1:2015) has recommended a minimum clear cover of 65 and 80 mm (with 15mm allowance in deviation) for submerged zone for the above working life.

Based on the existing researches and international codes for the tidal and splash zones CTL is considered as 0.40% by weight of cement content. Using the experimental data of Kim *et al.* (2016), a relationship between time of exposure and depth at which critical threshold reached is developed (see Figure 4b-5d). From above equation D_{crit} corresponding to 50 and 100 years of exposure period is found.

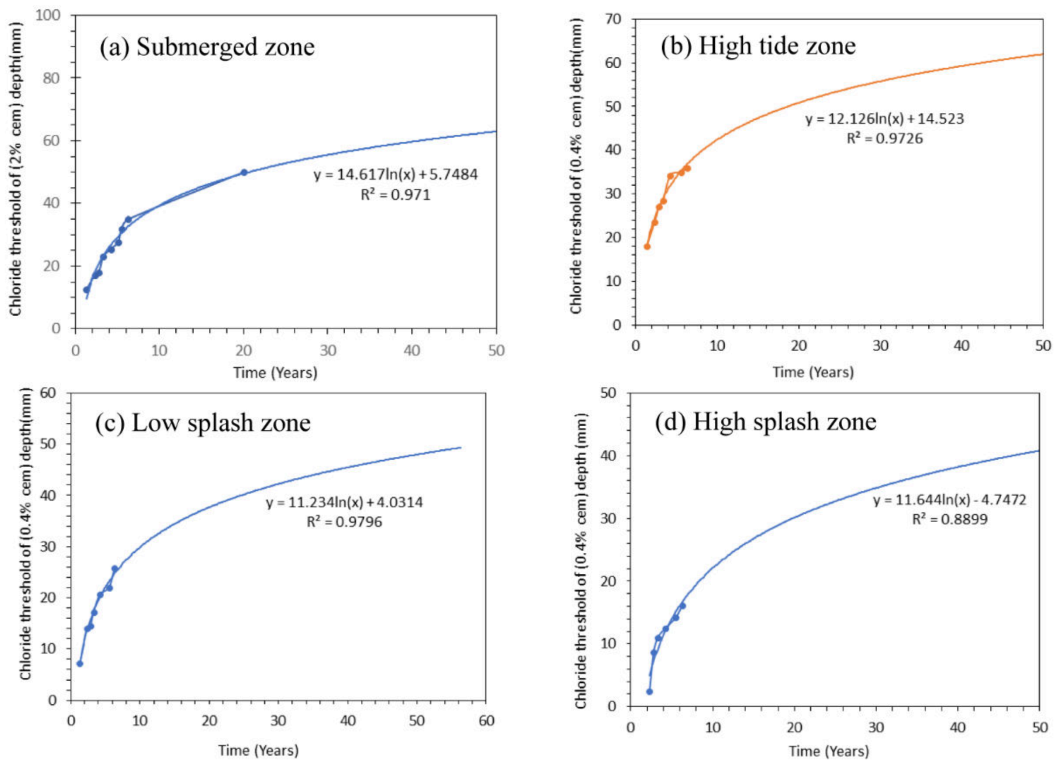

Figure 4: Simulation of CTL advance in concrete.

Exposure classes for chloride induced corrosion from seawater for Bangladesh

Considering severity of exposure conditions for concrete in contact with sea water two classifications namely W1 (*Concrete surfaces completely submerged and remaining saturated*) and W2 (*Concrete surfaces in the upper tidal zones and the splash and spray zones*) are proposed. For W1 and W2 the concrete properties align with *Extreme* and *Very Severe* category according to the exposure classification given in BNBC (2015). The tidal and spray/splash zones are predominantly severe and prone to long-term chloride corrosion with drying-wetting cycles because of the coupling effect of convection and diffusion of chloride. Hence, in the exposure conditions described in BNBC do not exactly portray the actual scenario of corrosion risk and thus needed to be revised.

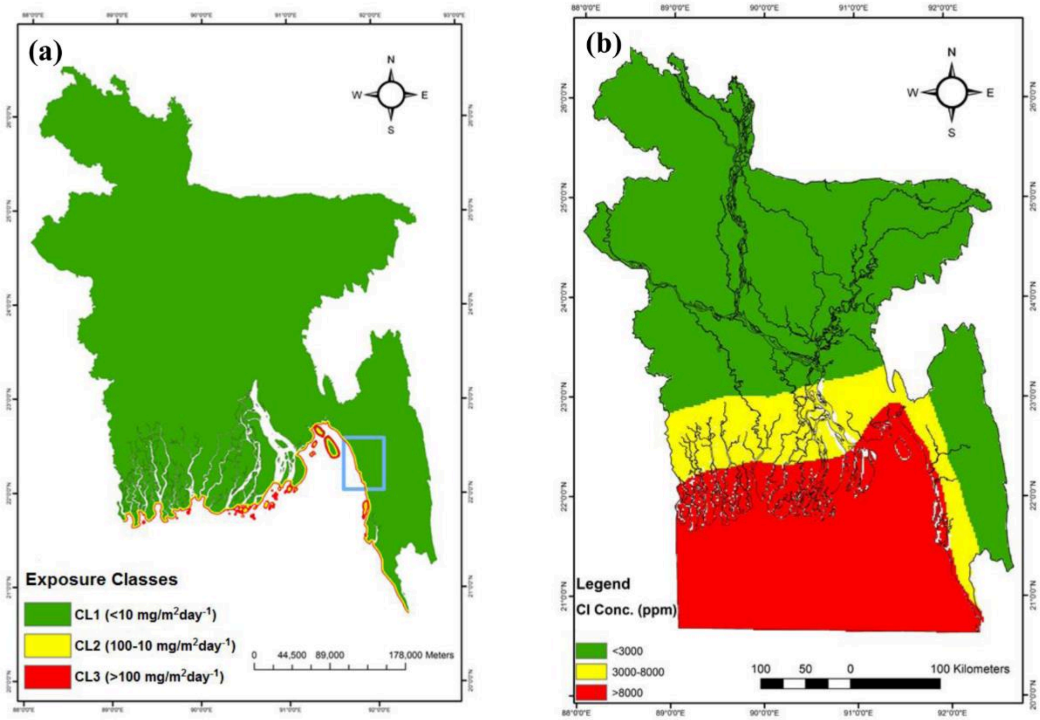

Figure 5: (a) Proposed exposure classes for atmospheric corrosion induced by chloride; (b) Sea/river water chloride concentration map for Bangladesh.

Table 1: Proposed concrete requirements based on exposure conditions for BNBC.

Exposure Classification	Exposure Conditions	Minimum f'c N/mm^2 c					
		25	30	35	40	45	50
		Nominal cover (mm)					
CL1	Reinforced and prestressed concrete structures with low or no risk to corrosion induced by airborne chloride situated beyond 1 km of coast		30	25	25	20	20
CL2	Reinforced and prestressed concrete structures subjected medium risk of corrosion induced by airborne chloride 0.10-1 km from coast.				40	35	30
W1	Concrete surfaces completely submerged and remaining saturated.				50	45	40
CL3	External reinforced and prestressed concrete surfaces in coastal areas endangered to within 0-0.10 km from coast.					50	40
W2	Concrete surfaces in the upper tidal zones and the splash and spray zones.						75
Maximum water/cement ratio		0.5	0.5	0.45	0.45	0.40	0.40
Minimum cement content, (kg/m^3)		325	350	375	400	410	420

Proposed exposure classes and concrete properties

The proposed exposure conditions and concrete properties for durability requirement in BNBC are compared with the international codes and researches. The suggested exposure classifications (Table 6.8.3) in Article 8.1.7.2 of BNBC (Vol. 2) is proposed as given in Table 5. The nominal concrete cover to reinforcement, maximum w/c ratio and minimum cement content required for various minimum concrete strengths to be applied in different exposure conditions are specified incorporating the results from previous sections. In addition, maximum water-soluble chloride ion (Cl^-) is proposed (Table 1) based on guidelines given by international standards and numerous researches conducted on chloride induced corrosion in marine structures.

CONCLUSION

The proposed BNBC could not properly define coastal zones affected by air borne chloride and tidal zone in exposure classification is missing. Following international trends and researches this study reclassified the marine exposure classes for Bangladesh and recommends durability requirements for these. Chloride map is prepared using GIS and divided into different zones incorporating severity of exposure. Based on the discussions, the following conclusions may be drawn:

- The definitions of exposure classes in BNBC have been expanded and made more rational by aligning them to the expected degradation mechanisms. Airborne chloride (CL) and chloride in seawater (W) exposures are proposed.
- Severity of airborne chloride is found to be within 1km of the coastal area. An empirical equation has been derived to predict the dry deposition of chloride in coastal regions with respect to local weather conditions.
- Considering CTL as 2% and 0.4% by weight of cement for submerged and tidal-splash zones, respectively empirical relationship has been derived to predict time and depth to reach CTL to determine minimum cover to reinforcement.
- Limiting values of concrete properties have been suggested based on the published research and available codes. These recommendations will require authenticating through laboratory tests for all the exposure conditions.

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REFERENCES

ACI Committee 318 (2014). Building Code Requirements for Structural Concrete and Commentary. *American Concrete Institute*, Farmington Hills, MI, USA.

Angst U, Elsener B, Larsen C K and Vennesland Ø (2009). Critical chloride content in reinforced concrete e a review. *Cement and Concrete Research*, 139(12), 1122–1138.

BNBC, Final Draft, (2015). Bangladesh National Building Code. *Housing and Building Research Institute*, Dhaka, Bangladesh.

Bureau of Indian Standard (BIS) (2000). Plain and Reinforced Concrete - Code of Practice. *IS 456(4th Rev.)*, (July), New Delhi, India.

Canadian Standards Association (CSA). 2014. A23.1-14/A23.2-14—*Concrete Materials and Methods of Concrete Construction/Test Methods and Standard Practices for Concrete*; CSA: Mississauga, ON, Canada.

Cole I S, Paterson D A and Ganther W D (2003). Holistic model for atmospheric corrosion. Part I - Theoretical framework for production, transportation and deposition of marine salts.

Corrosion Engineering and Science Technology, 38, 129-134

Domone P and Illston J (2010). Chloride-Induced Corrosion, 24.4.3, *Construction Materials Their nature and behavior*, 191-194.

EN ISO 9225 (2012). Corrosion of metals and alloys - Corrosivity of atmospheres - Measurement of environmental parameters affecting corrosivity of atmospheres, *European Committee for Standardization,* Brussels

Haque M N, Al-Khaiat H and John B (2006). Proposals for a draft code for designing durable concrete structures in the Arabian Gulf. *Arabian Journal for Science and Engineering*, 31(1), 205.

Hossain K M A, Easa S M and Lachemi M (2009). Evaluation of the effect of marine salts on urban built infrastructure. *Building and Environment*, 44(4), 713-722.

IRC 112 (2011). Code of Practice for Concrete Road Bridges. Indian Roads Congress, New Delhi, India.

Hossain K M A and Easa S M (2011). Spatial distribution of marine salts in coastal region using wet candle sensors. *International Journal of Research and Reviews in Applied Sciences*, 73, 228-232.

Kim J, McCarter W J., Suryanto B, Nanukuttan S, Basheer P A M, and Chrisp T M (2016). Chloride ingress into marine exposed concrete: A comparison of empirical-and physically-based models. *Cement and Concrete Composites*, 72, 133-145.

Kulkarni V R (2009). Exposure classes for designing durable concrete. *Indian Concrete Journal*, 833, 23–43.

Luping T and Utgenannt P (2008). Chloride ingress and corrosion from the Swedish field exposures under the marine environment, Workshop proceeding from a NORDIC Mini-seminar, Hirtshals, Denmark.

Meira G R, Andrade C, Alonso C, Borba Jr J C and Padilha Jr M (2010). Durability of concrete structures in marine atmosphere zones – The use of chloride rate on the wet candle as an environmental indicator*, Cement & Concrete Composites*, 32, 427-435.

Meira G R, Andrade C, Alonso C, Padaradtz I J and Borba Jr J C (2007). Salinity of marine aerosols in a Brazilian coastal area–influence of wind regime, *Atmospheric Environment*, 41, 8431–8441.

Meira G R, Andrade C, Alonso C, Padaratz I J and Borba J C (2008). Modelling sea-salt transport and deposition in marine atmosphere zone – A tool for corrosion studies, *Corrosion Science*, 50, 2724-2731.

Meira G R, Padaratz I J, Alonso C, and Andrade C (2003). Effect of distance from the sea on chloride aggressiveness in concrete structures in Brazilian coastal site. *Materiais de Construção*, Vol. 53, pp. 179-188.

Neville A (1995). Chloride attack of reinforced concrete: an overview. *Materials and Structures*, 28(2), 63.

Ragab A M, Elgammal M A, Hodhod O A G and Ahmed T E (2016). Evaluation of field concrete deterioration under real conditions of seawater attack. *Construction and Building Materials*, 119, 130-144.

Ramalingam S and Santhanam M (2012). Environmental exposure classifications for concrete construction - A relook. *Indian Concrete Journal*, 8(5), 18–28.

Recommendation, RILEM Draft (1994). Draft Recommendation for Damage Classification of Concrete Structures. *Journal of Materials and* Structures, 27, 362-369.

Roy S K, Chye L K and Northwood D O (1993). Chloride ingress in concrete as measured by field exposure tests in the atmospheric, tidal and submerged zones of a tropical marine environment. *Cement and concrete research*, 23, 1289-1306

Schiessl P and Raupach M (1990). Influence of concrete composition and microclimate on the critical chloride content in concrete, in: C.L. Page, K.W.J. Treadaway, P.B. Bamforth (Eds.), *Corrosion of Reinforcement in Concrete*, Elsevier Applied Science, London UK, 49–58.

Standards Australia (AS), 2014. Concrete structures-Commentary (Supplement to AS 3600-2009). *Standards Australia Limited*. Sydney, NSW 2001, Australia.

Weerdt K D, Justnes H and Geiker M R (2014). Changes in the phase assemblage of concrete exposed to sea water. *Cement & Concrete Composites*, 47, 53-63.

Zhang H F, Zhang W P, Gu X L, Jin X Y, Jin N G (2016). Chloride penetration in concrete under marine atmospheric environment – analysis of the influencing factors, *Structure and Infrastructure Engineering*, 12(11), pp. 1428–1438.

Results Follow Process: Leveraging the Integrated Design Process (IDP) to Fundamentally Change and Improve How We Design Infrastructure

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ABSTRACT

People are the key difference between mediocre and innovative infrastructure projects. Sustainable infrastructure design requires more than simply assessing a project against a sustainability scorecard or rating system. As a practice, sustainable design begins with people and their dynamics as a collaborative team. Decades of green building performance have taught us that optimized building design is only possible though an integrated process. Today, as infrastructure owners grapple with public perception, enhanced performance requirements, lifecycle impacts, and more, these lessons are more important than ever before, and should be leveraged by infrastructure designers. Due to the complex and diverse nature of infrastructure projects, traditional design approaches and delivery models make it challenging to fully realize the benefits of sustainable design. To successfully implement sustainable practices, design teams must employ innovative strategies through leveraging tools such as integrated design process, collaborative decision making, and sustainable design frameworks. Using “charrettes” to bring the broad team together for focused design and decision-making workshops is an important part of this process. Involving a construction manager early is also key to this approach, enabling integration of contracting and constructability knowledge into early planning and design. By examining a real project example, this paper will explore the benefits of taking an integrated design approach, involving a multidisciplinary collaborative team who work and make decisions together based on a shared vision and holistic project understanding. We find this approach leads to higher performance across a wide-variety of well-defined environmental and social goals, while staying within budgetary and scheduling constraints.

INTRODUCTION

What is the key difference between mediocre and innovative infrastructure projects? It’s simple, people. How people work together to develop innovative design, however, can be complex without a thoughtful approach.

Sustainable infrastructure design requires more than simply assessing a project against a sustainability scorecard or rating system. It begins with people and their dynamics as a collaborative team. Decades of green building performance have taught us that optimized building design is only possible though an Integrated Design Process (IDP). Today, as infrastructure owners grapple with public perception, enhanced performance requirements, and lifecycle impacts, this lesson is more important than ever before and can be leveraged by infrastructure designers.

Traditional design approaches and delivery models make it challenging to fully realize the benefits of sustainable design within the complex and diverse nature of infrastructure projects. To successfully implement sustainable practices, design teams must employ innovative strategies through leveraging tools such as integrated design processes, collaborative decision making, and sustainable design frameworks.

Integrating a multidisciplinary collaborative team early in a project to develop a shared vision and holistic project understanding enables it to effectively prioritize goals and make strategic directional, decisions. Using "charrettes", focused working sessions, throughout the project to bring the broad team together to progress design and make decisions is an important part of this process. Involving a construction manager early is also key to this approach, enabling integration of contracting and constructability knowledge into early planning and design.

This approach has been found to lead to higher performance across a wide variety of well defined environmental and social goals, while staying within budgetary and scheduling constraints (Busby Perkins+Will and Stantec, 2007). The results of IDP implementation are currently being experienced first-hand on the YVR CORE Program. CORE is one of the largest projects Vancouver Airport Authority (YVR) has ever undertaken; it is a $610 million high-profile infrastructure upgrades program which includes utilities and transportation components. IDP is being delivered through effective facilitation and active engagement of the design team, including the construction manager, cost consultant, engineers, architects, project managers, and various internal and external stakeholders as collaborative partners in the sustainable design for this project.

Developing sustainable infrastructure is vital for the health and longevity of our communities. Bringing together expertise across disciplines to collaborate, ask the right questions, prioritize the most important goals, and strategically guide design decisions just makes sense. Through the facilitation of IDP, we make the most of our infrastructure investments and develop sustainable solutions that empower our communities to flourish.

THE PROCESS

Concept of IDP

So where does the concept of IDP come from? IDP originated in the green buildings industry over two decades ago, adopted formally on many high-profile sustainable building projects including Natural Resource Canada's C-2000 pilot program in the early 1990s (Larrson, 2009). An example of this that Alex Zimmerman speaks to in the *Integrated Design Process Guide* for the Canada Mortgage and Housing Corporation, is Mountain Equipment Co-op's green buildings policy which requires design teams to implement IDP for each new store in order to achieve its laudable sustainable performance targets (Zimmerman, n.d).

When it comes to civil infrastructure, IDP is relevant, although more complex to implement at times. Applying IDP to infrastructure comes with a whole new host of challenges given the size, scale, timeframe, and complexity of these projects. Although infrastructure projects can be more challenging, the benefits of using an integrated design process from project onset can also be more pronounced.

In the design process for buildings and infrastructure, the most cost-effective time to implement sustainable design principles, discover synergies, and accommodate stakeholder and end-user needs is during preliminary and schematic design (Zimmerman, n.d.). Once a project has progressed to the final stages of design and construction and eventually operations it becomes challenging to make changes and the cost of re-design can be prohibitive. As a result, during early design, there is the largest opportunity to influence project performance, including sustainability.

In order to facilitate integrated design, upfront effort is required from the entire design team – including designers, the client, select stakeholders, contractors, and select industry experts and specialists (as outlined in *Figure 1*). By front-loading efforts during planning and early design, project teams are able to find synergies, cost/time efficiencies, and help clients realize benefits over the entire project lifecycle. Additionally, a collaborative process helps form relationships between the designer, contractor, the end-user which may often result in a design that is more constructible and easier to operate and maintain. This also reduces the likelihood of redesign or retrofit once construction or operations is underway.

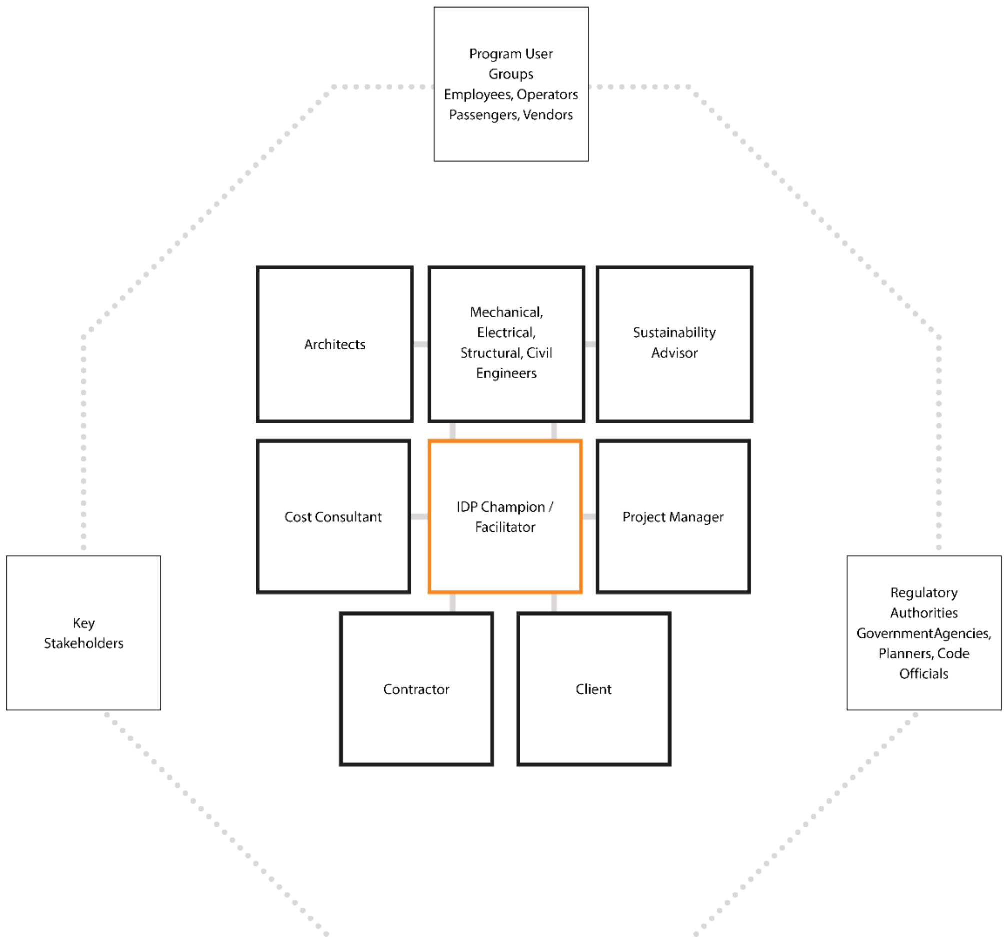

Figure 1. Example organization chart for an Integrated Design Process project.

IDP is an iterative approach to planning and design facilitation that supports and defends the creation of project alternatives and the analysis which allows for a robust and comprehensive decision-making process. Through facilitating a series of charrettes or workshops throughout design, the project process is bolstered by bringing together many disparate stakeholders within a transparent and inclusive process to ensure that the most suitable approach is undertaken, that all the necessary voices are heard, their ideas incorporated, and that the process is well-documented and defensible.

The Value of Bringing the Whole Team Together

So often in the design process, we begin design with the technical people – the engineers and the architects. These technical experts are, of course, essential to the design process. However,